STRATA ENGINEERING CORP.
RESEARCH . ENGINEERING . SCIENCE

Tel: (416) 441-2560
Suite 410, 170 The Donway West,
Don Mills, Ontario, Canada M3C 2G3
Telex: 06-966637, Fax: 416-~~449-2862~~ 441-4161

A REVIEW AND EVALUATION OF STRATA REINFORCEMENT TECHNIQUES COMBINED WITH OVERCORING METHODS TO DETERMINE IN SITU STRESS REGIMES IN COAL AND WEAK COAL MEASURES STRATA

DSS Project No. 15SQ.23440-7-9151-01-SQ

FINAL REPORT

March 31, 1988

MICROMEDIA

143 pp.

Distribution:

CANMET - 15 Copies
Strata File (S-87-200) - 1 Copy

EXECUTIVE SUMMARY

Depletion of shallower coal reserves demands improvements in analytical techniques to safely design underground openings associated with deeper coal mining. Critical factors for the efficient, safe and profitable design of underground openings, support systems, and pillars include a knowledge of the natural in situ state of stress of the rock mass.

A large number of in situ stress measurement techniques are available. They include overcoring. However, overcoring is very difficult to apply in weak coal measures strata because core disking and breakage result in an abnormal amount of test failures. Furthermore, the requirement for modelling the cored mass as an elastic continuous medium can not be satisfied for discontinuous jointed coal. Although they have not been tried previously, a potential solution to these problems is the use of strata reinforcement techniques.

The objective of this research was to study the feasibility of using strata reinforcement techniques prior to overcoring in weak coal measures strata. The study included a review of available stress measurement gauges and a variety of grouts which might be used in coal mining. This report reviews and evaluates the potential in situ methods applicable to weak coal measures strata, with particular emphasis on strata reinforcement overcoring techniques (STROT).

The study shows the ANZSI stress measuring gauge to be the most promising instrument for overcore testing in coal, especially when combined with aminoplast grout strata reinforcement. Two strata reinforcement methods are being recommended for further R&D verification - the central grout hole (CGH - STROT) method and the radial grout hole (RGH - STROT) method. A phased-approach R&D program is recommended to prove the effectiveness and efficiency of STROT in weak coal measures strata. Spin-off benefits are many, particularly for the Canadian coal mining industry.

RÉSUMÉ PRINCIPAL

En raison de l'épuisement des réserves peu profondes de charbon, il est nécessaire d'améliorer les techniques analytiques afin de créer des ouvertures souterraines sécuritaires liées à l'exploitation de la houille plus profonde. Il faut connaître l'état des contraintes in situ de la masses rocheuse pour déterminer les facteurs essentiels à l'efficacité, la sécurité et la rentabilité des ouvertures souterraines, des systèmes de soutien et des piliers.

Il y a nombre de techniques de mesure de la contrainte in situ, notamment celle du surforage. Le surforage est cependant trés difficile à utiliser dans les couches à faible teneur en charbon puisque les disques de forage et la rupture sont à l'origine d'un nombre anormal d'échec des essais. De plus, on ne peut répondre à l'exigence de moulage de la masse forée en un medium élastique continu en raison de charbon fissuré discontinu. Bien qu'elles n'aient jamais été éprouvées, le recours à des techniques de renforcement des couches constitue une solution potentielle.

L'objectif de ces recherches était d'étudier la faisabilité de l'usage de techniques de renforcement des couches avant le surforage des couches à faible teneur en charbon. L'étude comprenait un examen des indicateurs disponibles de mesure des contraintes et une variété d'injections que l'on pourrait utiliser dans l'exploitation de la houille. Ce rapport étudie et évalue le potentiel in situ des méthodes applicables aux couches à faible teneur en charbon, en mettant particulièrement l'accent sur les techniques de surforage pour le renforcement des couches (STROT - l'acronym anglais).

L'étude révèle que l'indicatuer permettant de mesurer la contrainte ANZSI sera l'instrument de plus prometteur pour les essais de surforage dans le charbon, particulièrement lorsqu'allié au renforcement des couches par injection d'aminolplaste. On recommande deux méthodes de renforcement des couches pour une meilleure vérification de R & D, la méthode du trou d'injection central (C G H - STROT) et celle du trou d'injection radiale (R G H - STROT). On préconise également la mise en place d'un programme de R & D graduel afin de prouver l'efficacité et le rendement de STROT dans les couches à faible teneur en charbon. Les avantages de stimulation sont nombreux, particulièrement pour l'industrie de l'exploitation de la houille.

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DSS Project No. 15SQ.23440-7-9151

Final Report

1.0 INTRODUCTION

Recent coal mining requirements for higher degrees of safety and reliability in the design and construction of deeper workings have prompted a need for greater knowledge about the nature and magnitude of in situ stresses, in the coal itself, for the prediction of structural stability. For example, studies aimed at improving the stability of access roadways for a longwall coal mining panel would benefit substantially from an accurate knowledge of the in situ state of stress in the coal through increased extraction, increased production efficiency, optimization of strata control, and increased safety (Erer and Heidarieh-Zadeh, 1985). Therefore, reliable and accurate in situ stress measurement techniques are needed, especially for coal and weak coal measures strata.

The importance of measuring stresses in coal, rather than in the more easily measured roof or floor rocks, is generally not appreciated. It can be readily shown that both the magnitude and direction of the normal stress at the coal-rock interface are significantly altered when the principal virgin stresses are not oriented parallel and normal to the seam, such as with dipping coal seams (Blackwood, 1976). In addition, stress measurements must often be confined to the coal seam if the roof and floor rocks are relatively soft and unsuitable for overcoring stress measurement techniques (Mills, Pender and Depledge, 1986).

Therefore, in order to study or analyze its behavior as a structural material, it is desirable to measure the state of stress in the coal itself. This need has been recognized by CANMET through its scientific and technological leadership and interest in the development of the Canadian coal mining industry, particularly in Sydney, Nova Scotia.

In November 1987, Strata Engineering Corporation was selected by CANMET/EMR to evaluate, by means of a literature review, strata reinforcement techniques combined with overcoring methods which might be applicable in coal and weak coal measures strata.

This report presents information in the following areas of literature search:

- background on coal seam features and the state of stress expected in coal mines;
- current in situ stress determination technologies, and their applicability to coal and weak coal measures strata;
- potential techniques of strata reinforcement for in situ stress determinations, including grout selection, reinforcement details, laboratory and theoretical data requirements, pumping pressures and equipment/expertise necessary to undertake such strata reinforcement procedures;
- a phased program of field and laboratory based research and development, to demonstrate and validate in situ stress measurements using strata reinforcement and overcoring techniques (STROT);
- a summary of current and future Canadian coal industry needs for the determination of in situ stresses in coal measures strata.

2.0 COAL SEAM FEATURES

This Section deals with coal seam features, and the properties of the Sydney Coalfield in particular.

Coal seam features are the result of their depositional setting, genesis, and subsequent alterations. These features are significant for the prediction of in situ strength and expected core recoveries. In the four groups described below, coal seam features are classified according to their origin.

2.1 Formation

These are seam features whose origins are related to depositional mechanics, morphology, and syngenetic fabrics. These features affect strata mechanics, ground control measures, and mining methodology but are of little interest in the context of this report. Formation coal seam features are not expanded upon here.

2.2 Petrography

Coal petrography is the most important element in the formation of transverse anisotropy in coal seams. The principal individual coal lithotypes are vitrain, clarain, fusain, durain, and black coal. There is a clear correlation between coal lithotypes and uniaxial compressive strengths. Table 1 shows the relationship between coal lithotype, density, and strength.

2.3 Rank

The rank of coal exhibits a known relationship to its strength and behaviour, which may depend upon changes in the composition of the coal caused by deposition and/or orogenesis. Every step in the gradual transition from organic material to various coals can be traced - from vegetation to peat, from peat to lignite, and so on to bituminous coal and anthracite.

Physical-mechanical characteristic	Hard coal	Semi-hard coal	Soft coal	Very soft coal
Lithology	Durain, cannel & boghead	Clarain, or composite of clarain, durain and vitrain	Vitrain	Fusain
Brightness	Dull	Semi-bright	Bright	Lustrous
Cleavage	Traces, or none	Irregular, erratic	Intensive, regular	Sheared, open fractures
Enlarged hole	0.3 to 0.5 D caliper deflection; walls of hole stable	1.0 to 1.5 D caliper deflection; hole caves with time	2.0 to 2.5 D caliper deflection; holes cave often	2.5 to 3.5 D caliper deflection; holes cave instantly
Density	Dense, structureless	Less dense, cracked	Low density, well cracked	Porous, with very low density
Uniaxial compressive strength	20 to 40 MN/m^2	7 to 18 MN/m^2	1 to 7 MN/m^2	0 to 1.0 MN/m^2

D = drillhole diameter

Table 1: Classification of lithotypes by hardness. (Jeremic, 1985)

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It is important to note that the classification of coal rank by strength criteria can not be generalized for all coal deposits.

Coalification is the main factor in the formation of various coal ranks. The principal causes of coalification are overburden depth and pressure, temperature, and time. These causes can be categorized into events, as follows:

2.3.1 Coalification events

Coalification events are processes which cause the transformation of vegetable matter into various types of coal. These include:

1) Biochemical - the alteration of plant material into peat due to microbial and associated chemical processes;

2) Diagenetic - the conversion of peat into lignite (soft brown coal) due to self-weight compaction and decrease in porosity, and chemical processes resulting in a 60 % increase in the carbon content of the organic material;

3) Metamorphic - a key factor in the formation of the higher rank coals through generation of mobile products (gas and crude oil) which leave in situ solid residues in the form of coal or keregon. Changes in the amount of hydrocarbons, hydrogen, volatile matter, carbon and methane gas present in the residue results in its transition from sub-bituminous coal, to bituminous coal, to coking coal, anthracite, and meta-anthracite.

2.3.2 Core recovery of various coal ranks

Core recoveries vary with coal rank. Typical values are shown below:

Excessive strength anthracite	< 90 %
Moderate strength high volatile bituminous & sub-bituminous	> 75 %
Low strength medium volatile & low volatile bituminous	< 50 %
No strength sheared low volatile bituminous & weathered high volatile bituminous or sub-bituminous	0 %, sludge

2.3.3 Mechanical stability of coal rank

The mechanical stability of coal seams and their behaviour under load is very important in strata mechanics and ground control. As mentioned previously, coal properties and coal rank should not be compared except within specific coal fields. An example of a comparison of the mechanical stability of coal seams of different rank for Western Canadian coalfields is given in Table 2. Supplementary data are given in Figures 1 to 4 showing idealized stress-strain diagrams for the various ranks. The classification of coal ranks and their relationship to mechanical properties is important because it might offer a qualitative estimate of the strength and mechanical stability of coal seams in a mine structure (Jeremic, 1980).

2.4 Cleats

The presence of cleats or structural defects in coal seams is promoted by a variety of factors including: depositional mechanics, coal petrography, coal rank, orogenic environment, and mining activities. These factors control the distribution, density and extent of jointing in coal seams. Cleat development is very significant in terms of overcoring, since cleats are generally the planes of weakness along which the overcore annulus usually breaks.

Cleats can be classified under three general cleavage groups:

1) Endogenous cleavage - mainly oriented perpendicular to the bedding planes; formed by internal forces arising from drying and shrinking of organic material, compaction, and release of volatiles;

2) Exogenic cleavage - oriented in the direction of the major principle stress and usually consisting of two sets of inclined joints; formed by external forces related to tectonic events;

Coal rank	Field observations		Laboratory investigations		
	Density of coal (gamma-gamma log)	Borehole phenomena	Compressive strength MN/m^2	Stress-strain relationship	Failure
Semi-anthracite	Very dense coal: 1.5–1.8 g/cm^3	Underground noise effect (similar to the tanderstorm), seismic effect (easy to record): large amount of gas release (bubbling flow of water at collar). After outburst, the hole is in collapsed state and its further drilling is abandoned	20–40	Elasto-brittle (Fig.1)	Violent release of strain energy
High volatile bituminous, sub-bituminous coal	Dense coal 1.3–1.5 g/cm^3	The borehole experiences enlarging its diameter (recorded by Caliper log) and larger content of the coal in drilling fluid (coal falling down in hole has been fragmented and lifted to surface by fluid circulation). No difficulties during exploration drilling	7–18	Elasto-plastic (Fig. 2)	Yielding with gradual release of strain energy
Low and medium volatile bituminous coal	Porous coal 1.1–1.3 g/cm^3	The borehole experiences closure deformation which can be very intensive if drilling was stopped in such a layer for a short period of time (for example 1 h). In this case, further drilling cannot be commenced because of closure of hole filled by soft coal	1– 7	Visco-plastic (Fig. 3)	Shear flow extrusion
Low volatile bituminous coal	Very porous coal: 1.0–1.1 g/cm^3	The borehole experiences blockage difficulties, because when coal layer is intersected the shear forces are activated, causing differential displacement. The hole under these conditions can be lost before the coal seam intersection has been drilled out	0–1	Plastic-friction (Fig. 4)	Fracturing, desitengration

Table 2 : Mechanical stability of coal seams of different rank. (Jeremic, 1985)

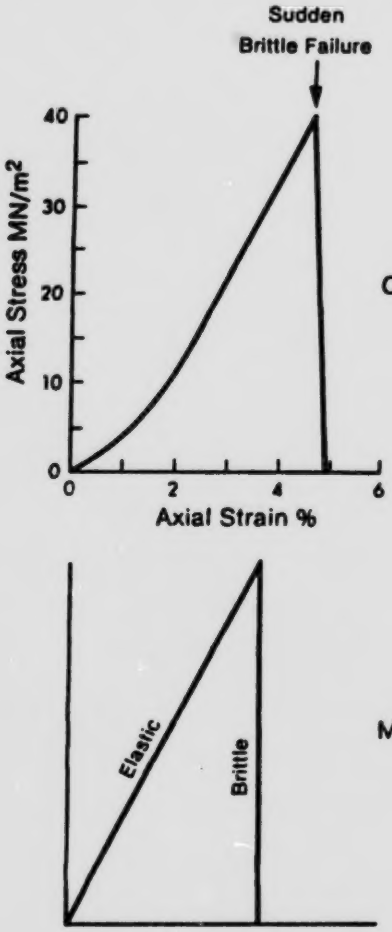

Figure 1 : Stress-strain diagram of coal of excessive strength.

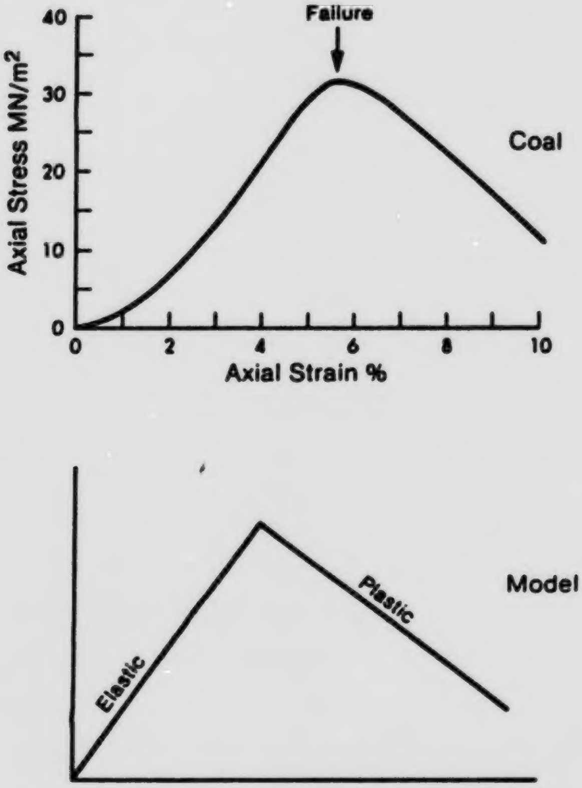

Figure 2 : Stress-strain diagram of coal of moderate strength.

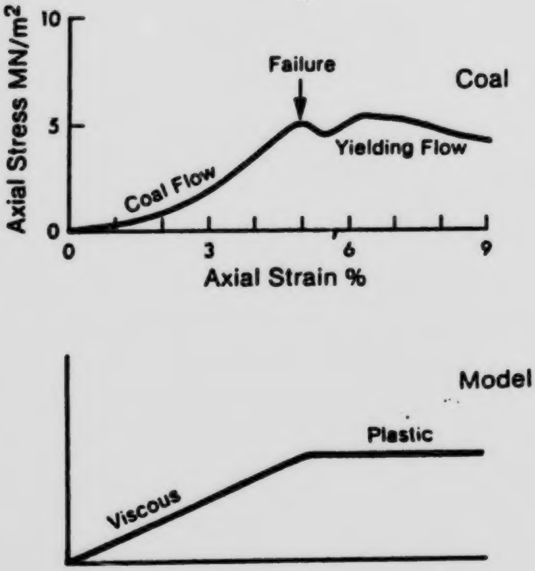

Figure 3 : Stress-strain diagram of coal of low strength.

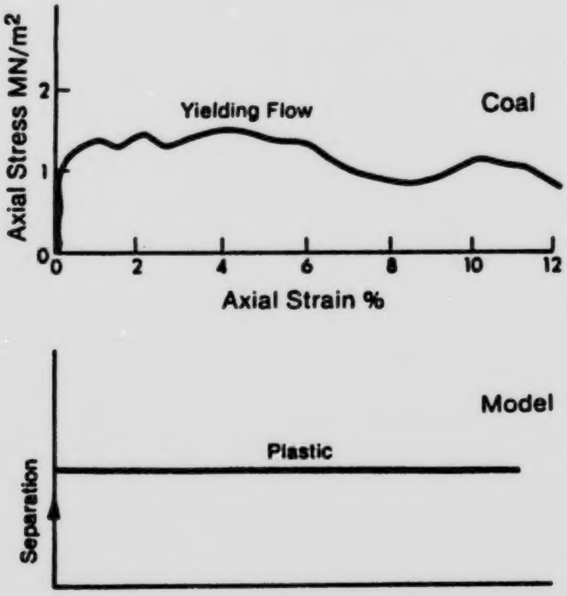

Figure 4 : Stress-strain diagram of coal of almost no strength.

(Jeremic, 1985)

3) Induced cleavage - originating from mining operations due to load transfer; this cleat type can not be easily distinguished from the other two.

For best results, overcore holes should be drilled in a direction perpendicular to the main cleat. This helps to prevent coal wedges from breaking off the rock annulus, and increases the likelihood of obtaining a solid rock core.

2.5 Sydney Coalfield Properties

The Sydney coalfield consists of coals that are Late to Middle Pennsylvanian in age and are ranked as high volatile "A" bituminous coal. Eleven major coal seams are present ranging from 1 to 4.5 m in thickness. Six seams are considered to be of economic importance (Forgeron et al., 1986).

The seams are separated by relatively consistent intervals of sandstone, siltstone, mudstone and minor shale, and limestone strata.

The coalfield has been tectonically disturbed. Some faulting has occurred, but the mining areas have generally been spared the effects of major faulting. The main structural features of the coalfield are its folds which plunge gently northeastwards.

The last major geological event to affect the coalfield occurred during the Pleistocene glaciation when a thin layer of glacial till was laid down on the erosional surface. Presently, the coastline is being actively eroded by the sea and many of the coal seams now outcrop beneath the ocean.

The cleat spacing in the Sydney coalfield is typically 2 mm.

From this information, it can be concluded that the Sydney coalfield consists of a semi-hard coal with moderate strength. The stress-strain relationship should follow an elasto-plastic model.

3.0 TYPES OF STRESSES ASSOCIATED WITH COAL MINES

The pressure concentrated within the earth's crust is referred to as "primitive" when it has not been disturbed by man-made openings. The determination of primitive pressures is complicated by our limited knowledge of the stress distribution as well as the geological history and the nature of the geological structures present. Strata pressures are often the result of interactions between several different stress fields. Two main types of primitive stress fields have been proposed (Jeremic, 1985):

1. Geological stresses - caused by such forces as the earth's gravitational field, orogenic movements, and glaciation;

2. Coal stresses - caused by changes in physical properties owing to different depths of strata.

These stress fields and their relationship to strata mechanics and mine stability are discussed in the following sections and are shown in Figure 5.

3.1 Geological Stresses

Underground coal mining operations are generally 300 to 600 m deep but may also be deeper than 1000 m. The strata are frequently deformed at these depths resulting in a complex distribution of stress. Regional stress fields influence the local distribution of stresses which affect mining operations. Therefore, a knowledge of the regional geology is necessary in order to understand the possible causes and orientation of stresses in mine strata. Natural stresses in the upper part of the earth's crust are the result of the integration of variable individual stresses.

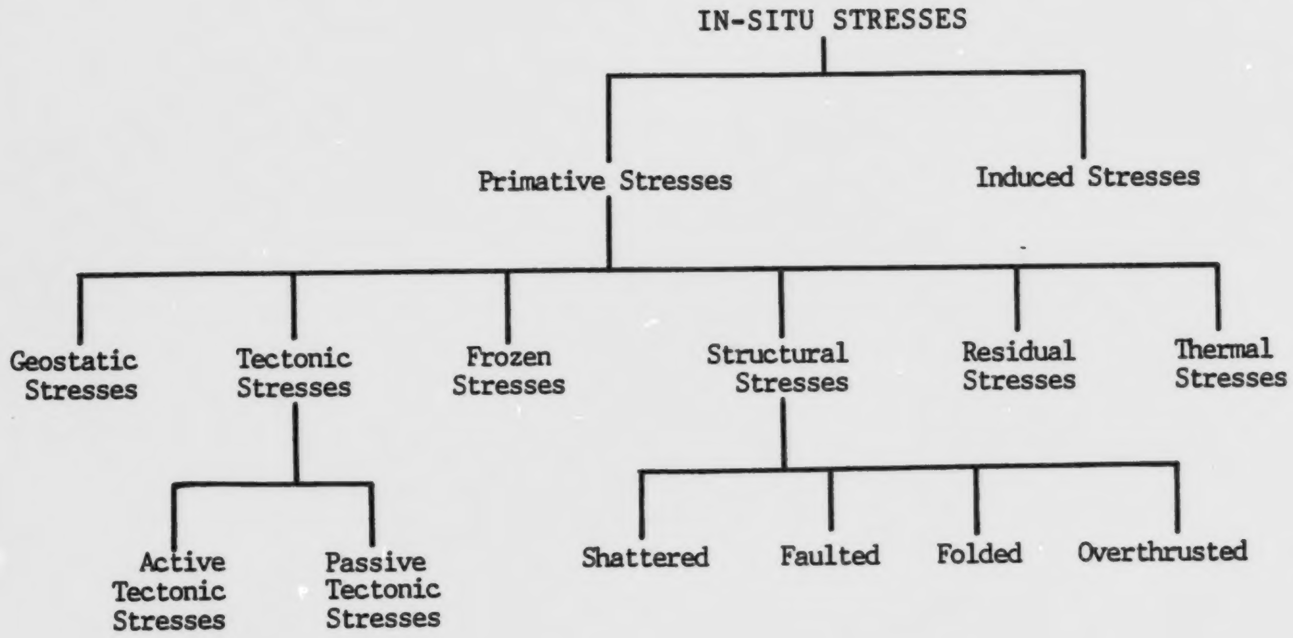
IN-SITU STRESSES
Primative Stresses
Induced Stresses
Geostatic Stresses
Tectonic Stresses
Frozen Stresses
Structural Stresses
Residual Stresses
Thermal Stresses
Active Tectonic Stresses
Passive Tectonic Stresses
Shattered
Faulted
Folded
Overthrusted

Figure 5 : Origin of in-situ stresses

3.1.1 Geostatic stresses

Geostatic stresses result from gravitational force and lateral constraint of the rock as shown in Figure 6. The magnitude of the geostatic stress is represented by the equation:

$$\Sigma_z = \gamma . h \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where, Σ_z = vertical geostatic stress

γ = unit weight of the rocks

h = depth below surface

The average unit weight, γ, for sedimentary rocks containing a coal seam is approximately 22 kN/m^3.

If the rock is isotropic, then the magnitude of the horizontal component of stress, Σ_x, varies with Poisson's ratio, v, as follows:

$$\Sigma_x = (v/1-v)\Sigma_z \ldots\ldots\ldots\ldots\ldots\ldots [2]$$

Poisson's ratio for coal can vary from 0.15 to 0.45, but it is generally taken to be 0.33 for underground mine design purposes.

It is important to remember that the vertical pressure, Σ_z, may also be influenced by tectonic stresses and may not be caused solely by the overburden weight.

3.1.2 Tectonic stresses

Tectonic stresses can be divided into two groups: active and passive.

3.1.2.1 Active tectonic stresses

Active tectonic stresses are related to earthquake phenomena arising from stress release at lithospheric plate boundaries. The direction of maximum compressive stress at these boundaries, as deduced from earthquakes and ground deformation, corresponds to the direction of relative motion of these plates.

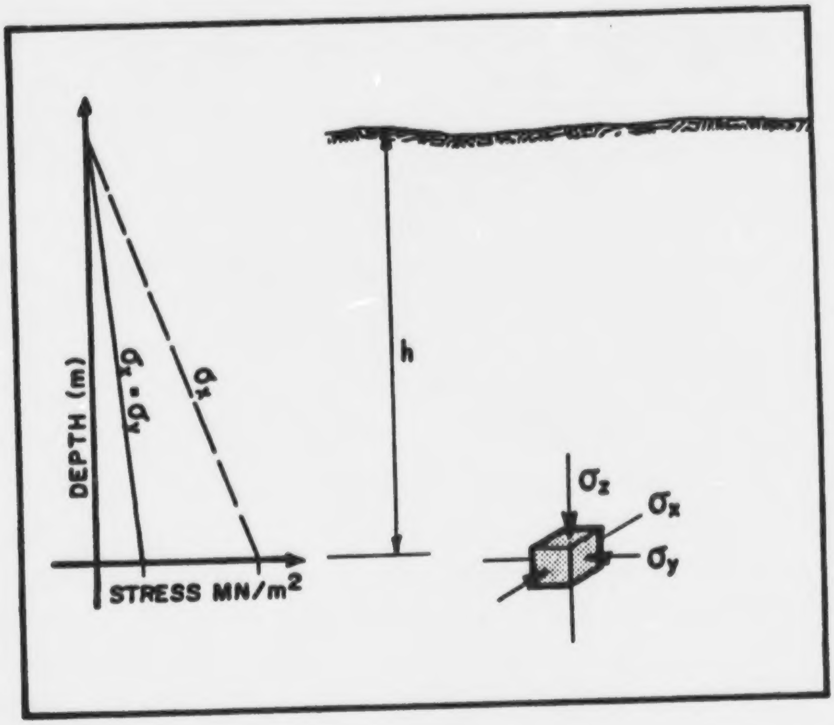
DEPTH (m)
STRESS MN/m^2
$\sigma_z = \sigma_y$
σ_x
h
σ_z
σ_x
σ_y

Figure 6 : Concept of state of geostatic stresses. (Jeremic, 1985)

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Away from plate boundaries, the active tectonic stresses are more difficult to analyze.

The increase in magnitude and redistribution of stresses both during and after earthquakes is well known, but is usually of short duration and varied in nature. This results in non-uniform and non-steady horizontal movements and uplifts which are difficult to predict. For this reason, active tectonic stresses are not usually taken into account in mine stability analyses.

3.1.2.2 Passive tectonic stresses

These consist of the remainder of the orogenic forces which were not spent on crustal deformation. These stresses are significant because they may be equal in magnitude, or greater than geostatic stresses. Residual tectonic stresses in coal bearing strata are mainly the result of orogenic movements due to uplift of the earth's crust. These stresses are usually classified by resolving the main compressive stress into two components: vertical and horizontal.

a) The existence of vertical tectonic stress has been recognized only very recently. Measured vertical stresses in coal basins are much greater than gravitational stresses (often up to 4.5 times greater). The presence of remnant tectonic stresses is most likely the cause for such a large discrepancy between gravitational stress and observed values. Unfortunately, it is very difficult to estimate the magnitude of these stresses.

b) Horizontal tectonic stresses have been investigated for at least two decades. In situ measurements within fold belts have shown the major principle stress (Σ_1) to be approximately perpendicular to the fold axis and the minor principle stress (Σ_3) to be parallel to it. Determination of the tectonic stress field in coal bearing strata is important to the efficiency and safety of coal mining operations; however, these stresses are difficult to separate from the total stress field.

3.1.3 Frozen stresses

Frozen stresses are usually found in coal basins which were not subjected to orogenic forces but were only affected by glaciation and erosion. The general model of frozen stress distribution is illustrated in Figure 7 and is briefly described below.

a) Loading of the coal formation was by slow sedimentary processes with a gradual increase in pressure. When accumulation was nearly completed, the pressure on the coal formation was hydrostatic at a depth of 4000 m or more. As water squeezed out, particles compacted, cement crystallized and the uncohesive rock mixture slowly petrified into a solid rock mass. During this process, a hydrostatic pressure of possibly 100 MN/m^2 was locked into the coal formation.

b) Unloading of the coal formation was by a slow process of uplift and erosion which removed a substantial portion of the overburden. As the load was removed, the rock expanded upward thereby relieveing some of the vertical stress. Relief of this stress was not in direct proportion to the load removed because of the elasto-plastic properties of the coal formation which stored part of the strain energy. Also, the lateral stress, which may have been as high as 100 MN/m^2 would remain locked into the coal formation because very little lateral expansion could occur.

In coal mines which have experienced only erosion and glaciation, it has been documented that the horizontal stress at shallow depths (50 to 150 m) can be three times greater than the vertical stress. In this situation, the magnitude of the compressive horizontal stresses in both the X and Y directions are approximately equal. Thus, it is important to consider frozen stresses separately from tectonic lateral stresses for the purpose of mine stability evaluation.

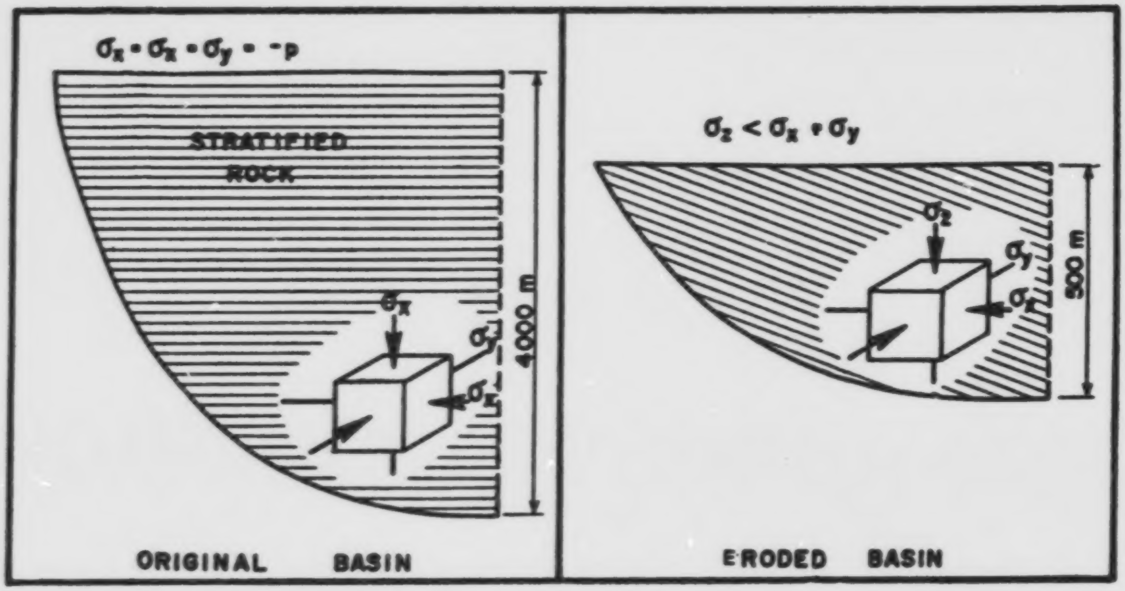

$\sigma_x = \sigma_x = \sigma_y = -p$
STRATIFIED
ROCK
σ_x
σ_y
σ_x
4000 m
ORIGINAL BASIN
$\sigma_z < \sigma_x = \sigma_y$
σ_z
σ_y
σ_x
500 m
ERODED BASIN

Figure 7: Concept development of frozen stress in rock strata. (Jeremic, 1985)

3.1.4 Structural Stresses

Structural stresses are very difficult to evaluate because they originate from tectonic deformation of the strata. Structural stresses can be classified into several groups which are related to particular types of geological structures.

3.1.4.1 Stresses of shattered strata

A fracture zone represents a more or less de-stressed zone with some limited bearing capacity.

3.1.4.2 Stresses of faulted strata

These are usually sources of violent deformations or bursting of the rock caused by accumulation of potential energy. The most violent rock bursts usually occur when headings are driven perpendicular to the fault zone in competent strata. Headings driven at low angles to such a zone gradually release the accumulated stress and eliminate the violent effects of bursting ground.

3.1.4.3 Stresses of folded strata

These stresses are caused in structural units which are bent and overstressed. As shown in Figure 8, there are additional stresses caused by flexural deformation in syncline and anticline structures. This is significant because roadways driven in the anticlinal portion of the folds have not experienced any adverse ground pressure; however, in synclinal portions, large scale floor heave has been exhibited due to high lateral compression.

3.1.4.4 Stresses of overthrusted strata

Overthrust strata exhibit two distinct zones of stress redistibution. The upper mobile thrust sheet is relieved of tectonic stresses but the lower stationary sheet exhibits a concentration of stress (Figure 9).

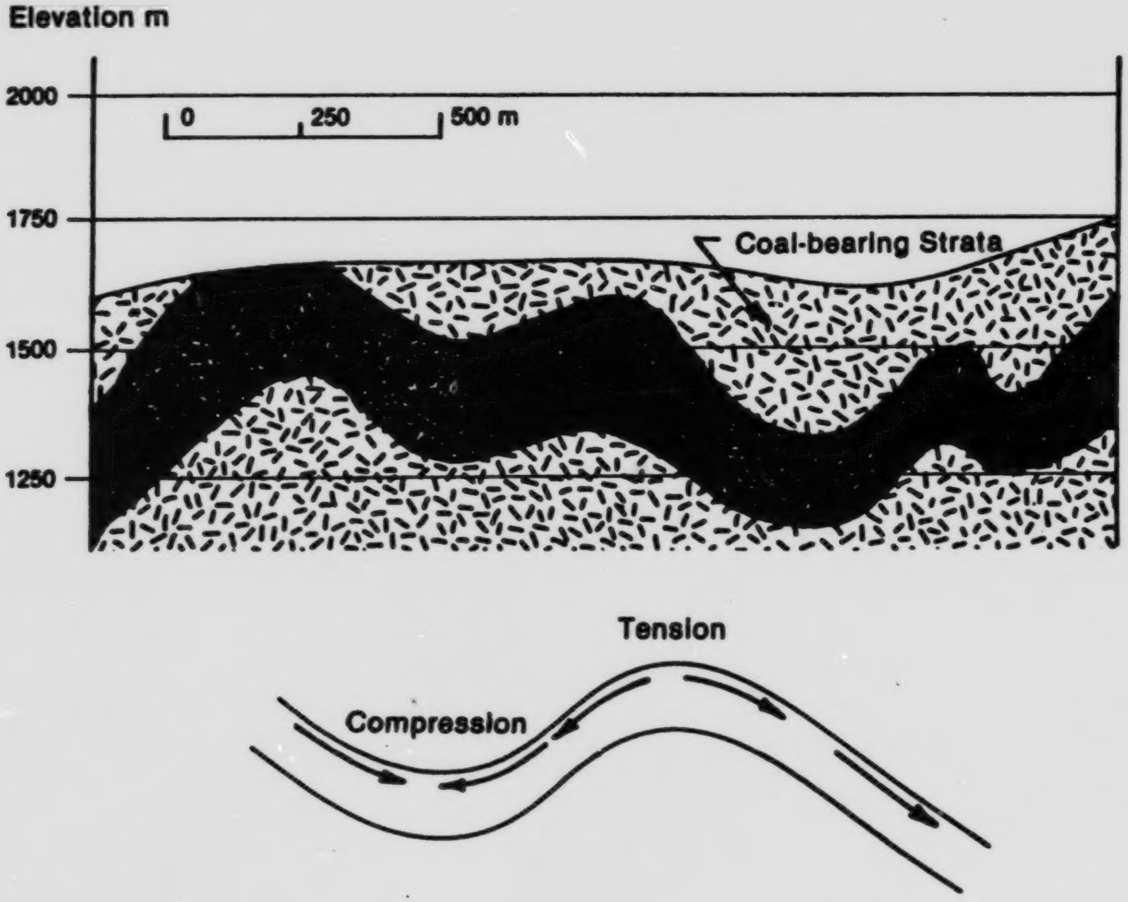

Elevation m
2000
1750
1500
1250
0
250
500 m
Coal-bearing Strata
Tension
Compression

Figure 8 : Overstress in folded strata (Cardinal River, Western Canada) (Jeremic, 1985)

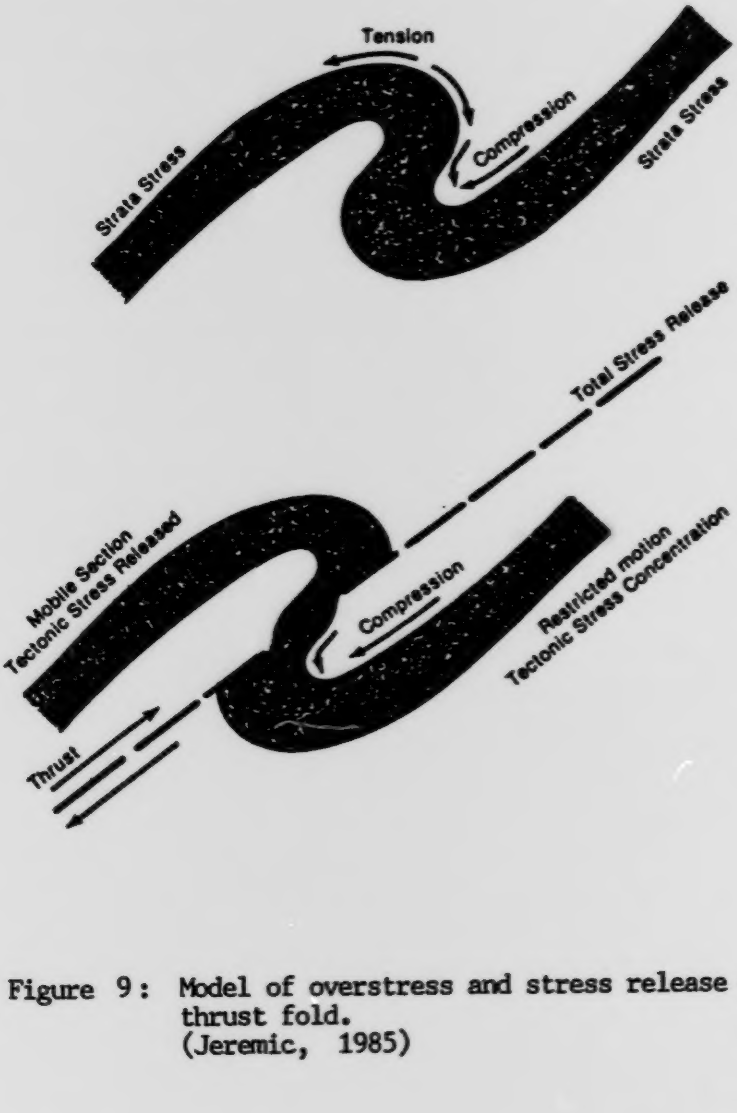

Tension
Compression
Strata Stress
Strata Stress
Total Stress Release
Mobile Section
Tectonic Stress Released
Compression
Restricted motion
Tectonic Stress Concentration
Thrust

Figure 9: Model of overstress and stress release of thrust fold.
(Jeremic, 1985)

3.1.5 Residual Stresses

Residual stresses have a local character and they remain in the rock strata after all external tectonic and gravitational forces are removed. The magnitude and orientation of these stresses are not well known.

3.1.6 Thermal Stresses

Thermal stresses depend on the state of strata stress, the properties of the rocks, and the thermal effects within the earth. These stresses, however, are not believed to play a major role in terms of the total stress field.

3.2 Stress State of Soft Coal Seam

In situ stress measurements in sedimentary strata show differences in the magnitude of stress in hard and in soft strata. Such stress differences arise from a load transfer between the softer and harder rocks. In situ stress measurements in virgin coal seams confirm such load transfers and indicate that the stress distribution within a coal seam is characterized by an equalization of the vertical and horizontal stresses regardless of the state of stress in the surrounding strata. Under these circumstances, a hydrostatic stress state is induced in the coal seams. In general, soft coal exhibits a decrease of strength and elasticity with an increase in mine depth.

There is a direct relationship between mine depth and the stress state in coal seams. The state of stress is also related to coal properties and behavior. Three types of behavior have been proposed for soft coal seams:

a) Shallow coal deposits are stress relieved and the coal exhibits a visco-elastic behavior (up to 250 m depth);

b) At moderate depth, the deposit is in a transitional stress state where a visco-plastic behavior predominates (250 to 450 m depth);

c) In deeper deposits, the coal exhibits viscous behavior indicating a hydrostatic stress state (over 450 m depth).

3.2.1 Stress relieved seams (shallow deposit)

The majority of shallow deposits are in a state of relieved stress through overburden removal by erosion. To simulate these states of loading and unloading, laboratory tests have been carried out by progressive loading of the samples and time dependent loading at constant load (Jeremic, 1985). The time dependent loading for constant load conditions suggests the following behavior:

- when a load is applied, the material is instantaneously strained. This is the elastic component of deformation;
- the strain rate increases with loading time after the instantaneous stress is exhibited. This is the viscous component of deformation.

The relationship between elastic and viscous strain can be expressed by a strain/time diagram (see Figure 10). This diagram shows that for different values of instantaneous strain, the intensity of viscous deformation varies. This phenomena suggests that the magnitude of viscous flow of coal increases with depth and that its shear strength decreases.

3.2.2 Transitional stress state

In situ investigations and laboratory tests for moderate loading conditions (up to 12 MN/m^2) suggest the following behavior of coal:

- The shear stress of the material decreases with depth while the per cent strain at failure increases;
- The shear stress equals the yielding stress, and further deformation follows a pattern of shear flow resistance.

The increase in shear strain rate with an increase in confining pressure suggests that the coal tends to be in a plastic-viscous state (Figure 11).

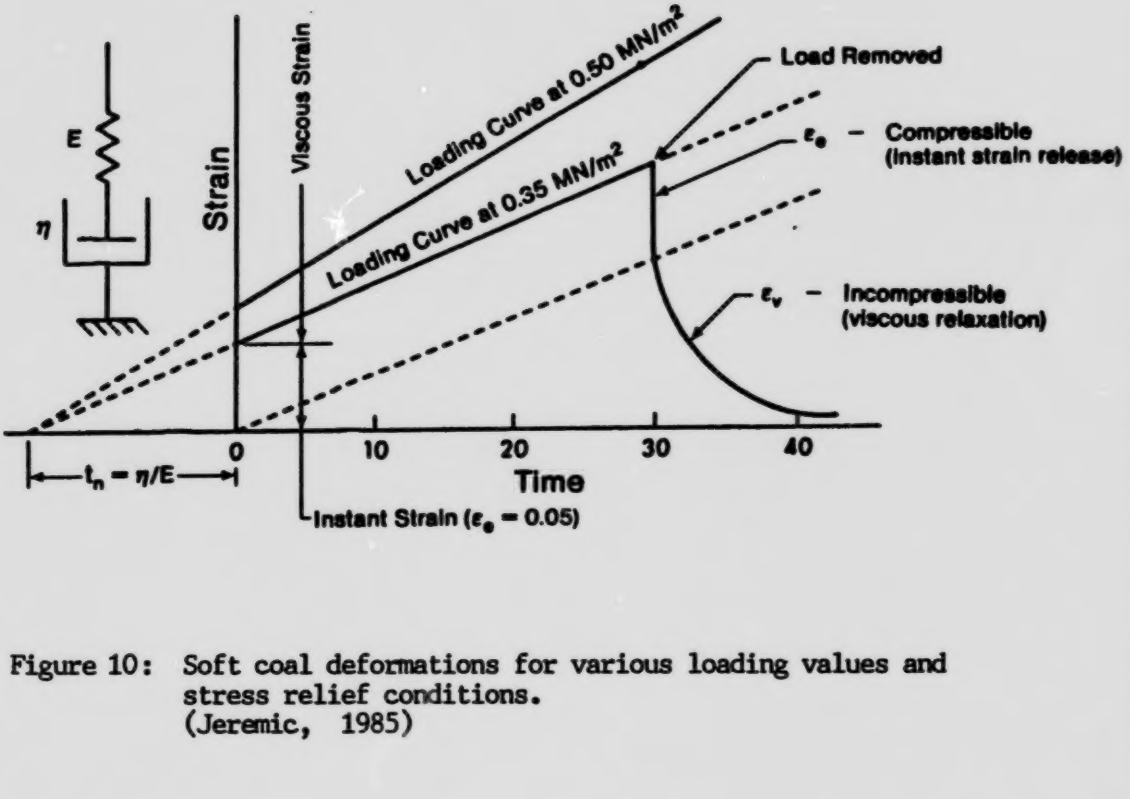


Figure 10: Soft coal deformations for various loading values and stress relief conditions.
(Jeremic, 1985)

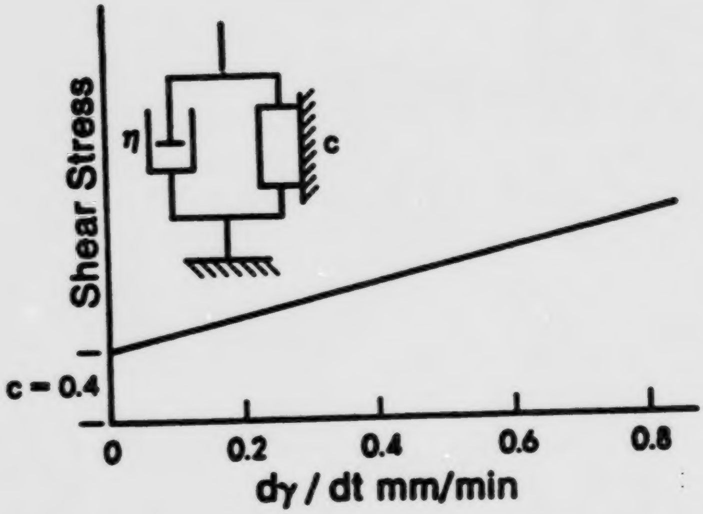


Figure 11: Resistance to flow at rupture.
(Jeremic, 1985)

3.2.3 Hydrostatic stress state

This state of stress may occur within coal seams at depths over 450 m. In laboratory investigations, it has been found that under large triaxial compressive loading, the horizontal and vertical components of stress become equal (Jeremic, 1985). Coal in such a hydrostatic state of stress is without shear strength. The relationship between the stress and strain is proportional to the coefficient of viscosity (Figure 12).

3.3 Summary of Stresses in Coal Mines

The geological history and the physical properties of the coal seam need to be considered before undertaking an in situ stress measurement program. A structural geologist familiar with the area should be able to piece together a geological history and estimate the magnitude and direction of the expected stresses. This information would also be useful in predicting the elastic properties of the coal seam.

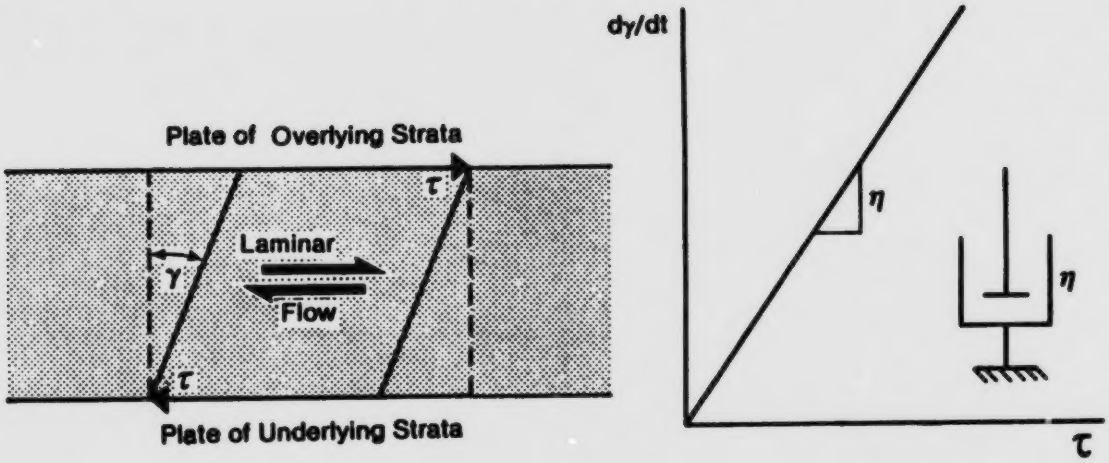


Plate of Overlying Strata
τ
γ
Laminar
Flow
τ
Plate of Underlying Strata
dγ/dt
η
η
τ

Figure 12: Viscous flow of soft coal for hydrostatic stress conditions. (Jeremic, 1985)

4.0 TECHNIQUES FOR MEASUREMENT OF IN SITU STRESSES

4.1 General

Stresses in situ can be measured in boreholes, outcrops, and in the walls of underground mines. The in situ stress measurement techniques presently available are summarized in Tables 3 and 4 for a wide range of rock types. These tables were first presented by Erer and Heidarieh-Zadah (1985) but are updated to include recently developed in situ stress measurement techniques.

The more popular and applicable methods for coal are described in later sections. Each method is described in great detail only if it is relatively new, since most of these techniques are already well known. The advantages/disadvantages as well as the effectiveness of each instrument or technique in coal and weak coal measures strata are also discussed.

The best known and most widely used in situ rock stress determination techniques are:

- overcoring
- hydraulic fracturing, and
- the flat jack method.

Each of these methods offers distinct advantages and disadvantages. The main problem with all such stress measurement techniques is that the measurement must be conducted in an area which will be disturbed by the process of gaining access for measurement. This problem is solved by accounting for the effects of such disturbance in the analytical stages of data interpretation. Similarly, if strata reinforcement techniques are developed, these too might influence the measured parameters. However, it may also be possible to account for such influences by analytical means.

Stress Measurement	Measuring Principle	Procedure	Name of Instrument	Transducer	Measurable Stress Component			Nature of Stress Meas.		Author/ Manufacturer	Country/ Year	Application to coal mining	Remarks
					1	2	3	abs.	rel.				
Stress Relieving	Measurement of changes in the diameter(s) of a borehole (Borehole Deformation Gauges)	Overcore the gauge within a central borehole	U.S.B.M. Deformation	Bonded strain gauges or Cantilevers	X (Year 1961)	X Year 1974	X Year 1967)	X		Merrill, Peterson, Hooker & Bickel	U.S.A. (1961)	Coal pillars	Soft inclusion currently available
		Overcore a solid cylinder with strain gauges	L.N.E.C. gauge	Bonded strain gauge rosettes	X		X	X		Rocha and Silverio	Portugal (1974)		Currently used. Araldite is used in the borehole
		Overcore a hollow cylinder with strain gauges	C.S.I.R.O. hollow inclusion cell	Epoxy bonded strain gauge rosettes			X	X		Worotnicki and Walton	Australia (1976)		
		Strain gauges encapsulated in a soft epoxy resin cylinder	Soft inclusion cell	Electrical resistance strain gauges			X	X		Blackwood	Australia (1976)	Rib pillars of longwall panels	Similar to LNEC gauge developed by Rocha
		Overcoring operation is carried out	Maihak vibrating wire cell	Vibrating wire transducer	X		X	X		Maihak Company	W. Germany (1960)		
			Griswold's cell	Strain gauges attached to cantilevers or rings				X		Griswold	U.S.A. (1962-3)	Not applicable	Out of date
			C.S.I.R. Mark I & II	I: electrical resistance strain gauges II: L.V.D.T.		X		X		Leeman (C.S.I.R.)	S. Africa (1960)	Coal pillars, not reliable	Out of date
			Sibek's cell	strain gauges		X		X		Sibek	Czecho-slovakia(1960)	Rib pillars and face	Out of date
			University of Liege cell	L.V.D.T.		X		X		Bonnechere	France (1975)		
			Four-comp deformation cell	strain gauges			X	X		Crouch Fairhurst (U.S.B.M.)	U.S.A. (1967)		Variation of U.S.B.M. triaxial cell
			Photo elastic soft inclusion cell	strain gauges		X		X		Riley, Goodman and Nolting	U.S.A. (1976-7)		
	Measurements of strains at the bottom face of a borehole (=borehole strain cells)	Overcore an inflatable soft inclusion instrument	ANZSI	strain gauges			X	X		Mills and Pender	New Zealand (1986)	Developed for coal measures rock	New method. Gives in-situ elastic modulus determination
		Overcore a rosette gauge bonded on the bottom of a hole	"Doorstopper"	bonded strain gauge rosette		X		X		Leeman (C.S.I.R.)	S. Africa (1971)	Applicable to coal measures rock	Very popular in many countries
		Overcore a borehole with strain gauges on its walls	C.S.I.R. Triaxial cell	bonded strain strain gauges			X	X		Leeman (C.S.I.R.)	S. Africa (1971)	Overcoring is difficult in coal	Determination of complete stress tensor in a single borehole
		Overcore a hemispherical rosette gauge bonded to the bottom of a hole	Hemispherical ended borehole technique	Bonded strain gauge rosette			X	X		Sugawara, Obara, Kaneko and Aoki	Japan (1986)	Applicable to coal measures rock	New method
	Strains at the bottom of a borehole	Overcoring operation	Photoelastic biaxial cell	Photoelasticity		X		X		Hawkes and Moxon	U.S.A. (1964)	Intrinsically safe for use in coal mining	Borehole should not exceed 5 m
			W.N.I.M.I. strain cell	Bonded strain gauges	X			X		Slobody	U.S.S.R. (1965)	It was used in longwall mining	Modified versions are being used
	Change in magnetic permeability with stress	Overcore a rectangular solid inclusion	Hast's cell	Magnetostriction	X			X		Hast	Sweden (1958)		The first reliable gauge employed
	Observation of photoelastic stress fringes	Overcore a hard inclusion with down hole polariscope	Photoelastic glass stressmeter	Photoelastic stress fringes		X				Roberts and Hawkes	U.K. (1964-5)	Applicable to longwall mining	Observations at fringes are difficult in deep boreholes
	Local relief in the side of a borehole	Measure the resultant displacement from drilling a small hole into the side of a borehole	Holographic stress measurement device	Interferometric device			X	X		Bass, Schmitt and Ahrens	U.S.A. (1986)	Suitable for coal mines	New method, unproven
	Stress changes	Use an optical technique to measure borehole deformation and transmit data via an infra-red signal	Borehole deformation gauge	Optical moiré fringe pattern		X		X		Blackwood and Buckingham	Australia (1986)	Applicable to coal measures rock	New method

Table 3: In-situ stress measurement techniques.

Stress Measurement	Measuring Principle	Procedure	Name of Instrument	Transducer	Measurable Stress Component			Nature of Stress Meas.		Author/ Manufacturer	Country/ Year	Application to coal mining	Remarks
					1	2	3	abs.	rel.				
Partial relieving of stress	Measurement of displacement caused by a slot cut wall (Stress compensation)		L.N.E.C. Flat-jack		X					Roche, Lopes and Silva (L.N.E.C.)	Portugal (1965)	Simply and effectively used	No grouting. Semi-circle slots. Reusable at increasing depths of same slot.
			U.S.B.M. Flat-jack	Electrical resistance strain gauges	X			X		Panek (U.S.B.M.)	U.S.A. (1961)	Applicable to coal measures rock	
			Cylindrical jack	Hydraulic oil within a core	X					Jaeger and Cook	U.S.A. (1966-9)	in coal pillars up to a depth of 15-18 m	Supplementary method
	Measurement of displacement of strain gauges due to undercoring	Undercore the strain gauge rosette on the surface of a rock face		Three pairs of strain gauges	X			X		Duvall and Hooker	U.S.A. (1974)		Variant of the "Doorstopper" installation is difficult supplementary method
	Cast inclusion method	Overcore a hard inclusion to freeze stresses into it	Soft inclusion gauge		X			X		Riley Goodman	U.S.A. (1977)		Stresses are measured in the laboratory
	Borehole deepening method	Monitor the radial deformation of deepening boreholes		Detection of bending cantilver: beams with bonded strain gauges	X			X		De La Cruz and Goodman	U.S.A. (1970)		Measurements should be performed as close as possible to the bottom
	Pressure-bag method	Locating the rubber pressure bag in the bottom end of a borehole drilled in a pillar	The rubber pressure bag	Displacement of a hydraulic fluid	X			X		Baar	W. Germany (1960)	easily installed in coal	
Measurement of stress changes by hard inclusions	Borehole inclusion stressmeter	Measurement of changes in transducing element due to rock stress variations	Potts' stressmeter	Electrical resistance strain gauges	X			X		Potts	U.K. (1960)	widely used in coal mines	
			Grid stressmeter	Strain gauges in the form of a wheatstone bridge	X			X		Salamon	U.K. (1960)		Not currently available
			M.R.D.E. borehole plug	Foil resistance strain gauges	X			X		Wilson	U.K. (1960)		
			Hast's rigid inclusion	Electrical res strain gauges	X			X		Hast	Sweden (1958)		
			Glass stressmeter	Photoelastic fringes		X			X	Roberts and Hawkes	U.K. (1964)	suitable for coal mines	Illumination difficulties may arise
			Spherical rigid inclusion	Three strain gauge rosettes			X		X	The U.S. Geological Survey	U.S.A. (1968)		Cell is grouted in the borehole
			Vibrating wire stressmeter	Vibrating wire			X		X	Hawkes	U.S.A. (1973)	Applicable to coal mines	
			U.S.B.M. encapsuled borehole hydraulic stressmeter	Close hydraulic circuit		X			X	Lu (U.S. Bureau of Mines)	U.S.A. (1981)		Favourable gauges at present
			PAL borehole stress meter	Strain gauges		X			X	Park	U.S.A. (1986)	Applicable to coal measures rock	New method. Easy installation
Rock fracture	Rock fracture	Hydraulic fracturing in a borehole				X		X		Fairhurst Haimson	(U.S.A.) (1965) and (1978)		Current stress measuring method
		Core discing			X			X		Obert and Stephenson	U.S.A. (1965)		
		Measure strain to fracture a borehole with a borehole jack			X			X		De La Cruz	U.S.A. (1978)		
Other stress measurement techniques	Correlation between rock properties and stress	Measure the velocity of sound in rock			X					Obert and Duvall	U.S.A. (1957)		Supplementary methods of stress measurement in rock
		Resistivity, rock noise			X					Kanagawa, Hayashi and Nakahara	Japan (1976)		
		Detection of yield point			X			X		Dreyer and Borchert	W. Germany (1957)		
		Isotope method			X					Borecki and Kidybinski	Poland (1966)		

Table 4: In-situ stress measurement techniques.

4.2 Overcoring Method of Stress Determination

In principle, a borehole under rock pressure is "stress relieved" by drilling a larger concentric hole (i.e. overcoring operation). The deformation of the inner hole, which is a function of the field stress, is measured to obtain the original state of stress within the rock. Application of overcoring to longwall coal mining requires careful consideration of the following points:

- drilling operations in coal measures strata, particularly the coal itself, requires special expertise. Overcoring operations in such strata need to be performed with great care to prevent core breakage; otherwise the entire work has to be repeated;

- a biaxial test should be performed on the rock annulus in order to determine its elastic properties; this requires an annulus of sufficient length from the overcore test;

- unlike hard rock, the inner wall of a borehole drilled in coal has a rough surface and is easily disturbed during instrumentation therefore an accurate measurement of changes in the borehole diameter is often difficult to determine;

- intrinsically safe electrical equipment needs to be employed;

- the existence of water in the borehole and its influence on strain readings needs to be taken into account;

- for epoxy bonded gauges, adhesion to coal measures rocks is difficult.

4.2.1 The overcoring technique

There are many types of overcoring techniques. However, they differ only as to the types of instruments used, and the manner in which they are installed. The actual overcoring method is essentially always the same.

The following is a summary of the overcoring technique:

- drill an HQ size hole to the desired depth and flatten its base;
- drill a small diameter EX size pilot borehole approximately 500mm past the flattened end;
- install an overcore instrument into the pilot borehole;
- drill a larger hole concentrically over the pilot borehole containing the installed instrument and monitor the data output from the installed instrument as the overcoring occurs;
- extract the overcored cylinder of rock (rock annulus);
- perform a biaxial test on the rock annulus.

From § (strain measured during overcoring), E (Young's modulus), v (Poisson's ratio), and ø (the borehole diameter), the initial state of stress, Σ_i, at the test location can then be determined.

In situ stress determinations are often inaccurate. Besides measurement inaccuracies, some measurements can be affected by the way the mechanical behaviour of the rock is modelled. Strains recorded during testing are usually related to the the rock stresses on the assumption that the rock behaves as a homogeneous, isotropic, continuous, and linearly elastic medium. Coal however, can not ideally be modelled with these characterisitics since it is an anisotropic, discontinuous material. Coal can also act plastically, in which case stress measurements based on an elastic model would be invalid. However, plastic deformation is mostly a problem with the weaker, medium and low volatile bituminous coals.

For measurements of change in strain, Δ§, it is possible to obtain at least six independent measurements in one borehole by orienting the strain rosettes in different directions. Thus, the complete state of stress can be determined within a single borehole by measuring changes in strain in six non-parallel strain gauges or by combining diametral and oblique measurements. This is valid regardless of the isotropic/anisotropic character of the rock and the orientation of the hole with respect to the planes and axes of elastic symmetry of the rock. When changes in the diameter, $\Delta 0$, only are measured (such as with the USBM gauge), it is possible to obtain the complete stress tensor with only two boreholes but in many circumstances a third borehole is required (Anadei, 1985). Table 5 lists the numbers of borehole required for specific cases.

Although it is difficult to draw conclusions for all types of anisotropy, it appears that neglecting anisotropy can create large errors in both the magnitude and the orientation of the in situ stress field assessment (Amadei, 1985). This is particularly true for moderate and strongly anisotropic rocks and for low values of the strike angle. In order to assess the influence of rock anisotropy on in situ stress measurements from a quantitative point of view, knowledge of the directional character of rock deformability is required through testing of rock specimens in the laboratory and in situ.

The various types of in situ gauges and stress measurement methods available are listed below, along with their advantages, disadvantages, and applicability to coal measures rocks.

4.3 In Situ Stress Measurement Gauges and Methods

4.3.1 USBM (United States Bureau of Mines) method

The USBM method (Merrill and Peterson, 1961; Hooker and Bickel, 1974) is a biaxial method that uses the bending of a cantilever equipped with strain gauges to measure deformation of the pilot hole across three diameters. Figure 13 shows a cross-section of a USBM deformation gauge.

Angle between the two boreholes	Isotropic Anisotropic Character of the rock	Orientation of both boreholes with respect to the planes and axes of elastic symmetry of the rock	Requirement for a third borehole
any	Anisotropic	Each hole is not perpendicular to a plane of elastic symmetry Figure 6.6f	No
Non Perpendicular	Anisotropic	Only one hole is perpendicular to a plane of elastic symmetry Figure 6.6e	
any	isotropic	----	Yes
90°	Anisotropic	Only one hole is perpendicular to a plane of elastic symmetry Figure 6.6d	
90°	Anisotropic	Each hole is perpendicular to a plane of elastic symmetry Figures 6.6 a,b	
any	Anisotropic	Both holes are within a plane of transverse isotropy Figure 6.6c	

Table 5: Number of boreholes required for the Determination of the Complete State of Stress from Diametral Measurements only.
(Amadei, 1985)

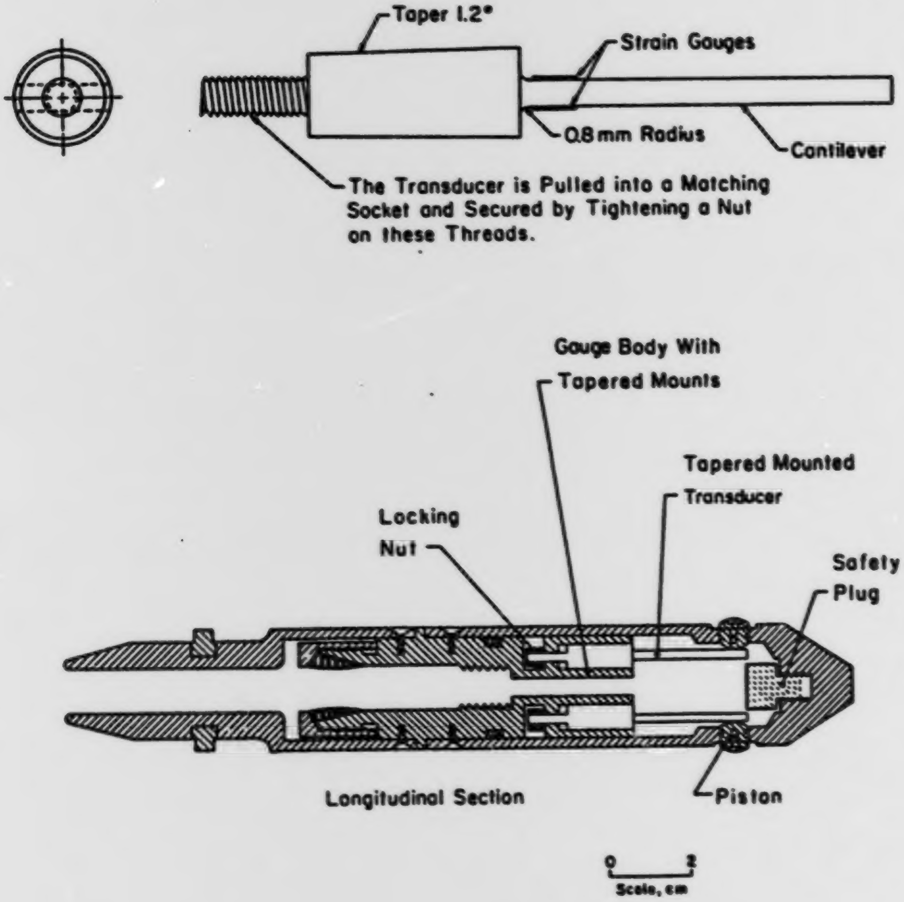

Taper 1.2°
Strain Gauges
0.8 mm Radius
Cantilever
The Transducer is Pulled into a Matching Socket and Secured by Tightening a Nut on these Threads.
Gauge Body With Tapered Mounts
Tapered Mounted Transducer
Locking Nut
Safety Plug
Longitudinal Section
Piston
0
2
Scale, cm

Figure 13: Cross-section through a United States Bureau of Mines deformation gauge.
(Szwilski, 1984)

4.3.1.1 Advantages

- the instrument is very rugged;

- it probably produces the most consistent overcoring test results;

- tests are very fast and installation is simple;

- the instrument may be re-used many times;

- it is stable compared to epoxy bonded devices because it is less affected by temperature changes in the rock or by the drilling water.

4.3.1.2 Disadvantages

- the stress field can be measured in only two directions. Therefore, in order to determine the complete stress tensor, measurements must be obtained from at least two non-parallel boreholes.

- The cantilever/strain gauge response to diametral displacement must be calibrated before use. This system has a resolution of measurement, after calibration, of about ± .001 mm, equivalent to ± 26 microstrain in a 38 mm (EX) hole (Blackwood and Buckingham, 1986). This is relatively insensitive when compared with electrical resistance strain gauges which normally have a resolution of ± 1 or 2 microstrain under favourable conditions (ie. no creep or amplifier drift).

4.3.1.3 Applicability

- the gauge can be used in only the more competent coal measures strata where the core will not disk during overcoring (Blackwood & Aust, 1973). Unlike epoxy grouted techniques, the USBM gauge adds no strength to the rock annulus. If disking does occur, the gauge could be damaged;

- the relatively stiff sensors of the gauge can penetrate softer coal or any discontinuities present in the borehole. This would give a slightly inaccurate value of diametral strain, as the effective diameter of the borehole is usually assumed constant (Szwilski, 1984).

4.3.2 CSIR (Council for Scientific and Industrial Research) method

The CSIR cell (Leeman, 1968) was the first triaxial overcoring instrument developed, and it is one which is still used extensively today. This cell consists of a metal or plastic body containing three rosettes. Each rosette contains three strain gauges mounted at various angles. The rosettes are cemented directly to the surface of the rock in the pilot hole, so as to monitor shear stresses created during overcoring. Figure 14 shows an exploded view of the CSIR triaxial strain cell.

4.3.2.1 Advantages

- the complete stress tensor can be determined from one borehole;
- approximately half the cost of the CSIRO cell;
- overcoring can take place only 1 hour after installation as compared to 12 to 16 hours for the CSIRO cell;
- the cement used to bond the CSIR rosettes to the borehole wall does not creep as do the epoxies used for the CSIRO cell;
- the three independent rosettes of the CSIR cell are less likely to de-bond from the rock during overcoring than the complete cylinder design of the CSIRO cell. The reason for this is that the stresses between the CSIR rosette and the borehole wall during overcoring are mainly shear stresses and are small in magnitude, whereas for the CSIRO cell, the stresses are tensile and large relative to the strength of the epoxy (Thompson et al., 1986).

4.3.2.2 Disadvantages

- the rock surfaces to which the rosettes are to be cemented must be extremely clean and dry in order to obtain a satisfactory bond;
- the gauge must be kept dry during overcoring. If wet, the gauge can be short circuited which results in erratic readings;
- in its original design, strain readings could not be made during overcoring. Only before and after overcore drilling could readings be taken. This is a disadvantage because it is very difficult to determine if the strain gauges are cemented well and working properly during overcoring.

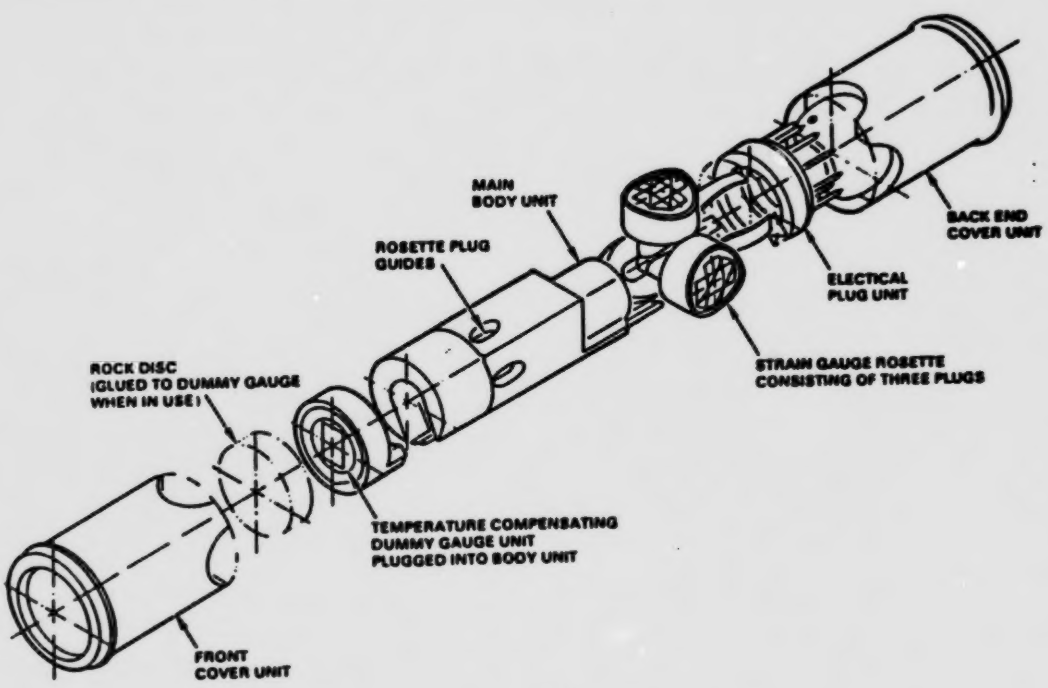

MAIN BODY UNIT
ROSETTE PLUG GUIDES
BACK END COVER UNIT
ELECTICAL PLUG UNIT
STRAIN GAUGE ROSETTE CONSISTING OF THREE PLUGS
ROCK DISC (GLUED TO DUMMY GAUGE WHEN IN USE)
TEMPERATURE COMPENSATING DUMMY GAUGE UNIT PLUGGED INTO BODY UNIT
FRONT COVER UNIT

Figure 14: Exploded view of the CSIR triaxial strain cell.
(ISRM, 1987)

This problem has been solved recently, however, by using a special installation head which allows strain readings to be taken during overcoring (Thompson et al., 1986);

- temperature compensation using a dummy rosette and bonded rock chip in half bridge configuration causes errors (Stillborg and Leijon, 1982).

4.3.2.3 Applicability

- this method is generally not used in coal because of the difficulty in cleaning and drying the pilot hole. It is also very difficult to cement the rosettes to coal;

- fractured coal may allow water into the pilot hole during drilling. This has a detrimental effect on the operation of the gauge.

4.3.3 Epoxy grouted overcore instruments

Three types of epoxy grouted overcoring techniques have been developed. Although all three of these gauges are completely epoxied into the borehole, there are slight differences in the construction of each of these gauges.

4.3.3.1 LNEC method

Rocha and Silverio (1969) developed the first of these gauges called the LNEC gauge (National Civil Engineering laboratory). They embedded strain gauges into a solid epoxy probe which was then epoxied into the pilot hole and overcored. This probe is best described as a rigid inclusion triaxial stress gauge because the elastic modulus of the inclusion is about twice that of the host rock. The major disadvantage of the solid probe is that, on overcoring, tensile stresses are developed at the epoxy/rock interface which may be sufficiently large to break the bond between the probe and the rock or perhaps even the rock itself. Blackwood (1977) used an epoxy with a low Young's modulus and succeeded in reducing these tensile stresses. This gauge, although used with limited success, has been virtually abandoned in preference for newer, improved versions.

4.3.3.2 Soft inclusion probe

Blackwood (1976) has developed a solid soft inclusion probe which has an elastic modulus less than that of the host rock. The gauge body is composed of epoxy resin compounds and has an elastic modulus of 1.0 GPa. This gauge differs from the CSIRO and LNEC gauges in that strains within the inclusion itself are measured rather than measuring rock strains directly. He has used this probe extensively in coal with good success. He also reports that the problem of epoxy/rock debonding, although expected in theory, does not occur in practice (Blackwood et al., 1986). From communication with experts in the stress measurement field, it appears that although Blackwood claims great success with this gauge, it is generally not accepted as a valid method for use in coal, and has not been extensively used in other parts of the world. Figure 15 shows a diagram of this instrument prepared for field use.

4.3.3.3 CSIRO method

Others have tried to overcome the problem of epoxy/rock bond failure in different ways. Rocha et. al. (1974) and Worotnicki and Walton (1976) developed independently a "hollow inclusion triaxial strain gauge", which is commonly known as the CSIRO (Commonwealth Scientific and Industrial Research Organization) cell. This instrument consists of nine or twelve electrical resistance strain gauges which are encapsuled in the wall of a thin walled epoxy pipe. Although this has the same effect as Blackwood's solution (ie. the modulus of the gauge is reduced), the problem of rock/instrument debonding may still occur in weak rock. Figure 16 shows a schematic layout of a CSIRO hollow inclusion cell and Appendix A contains information on this gauge.

The advantages, disadvantages and applicability of the CSIRO and the solid soft inclusion gauge for use in coal measures strata are listed below:

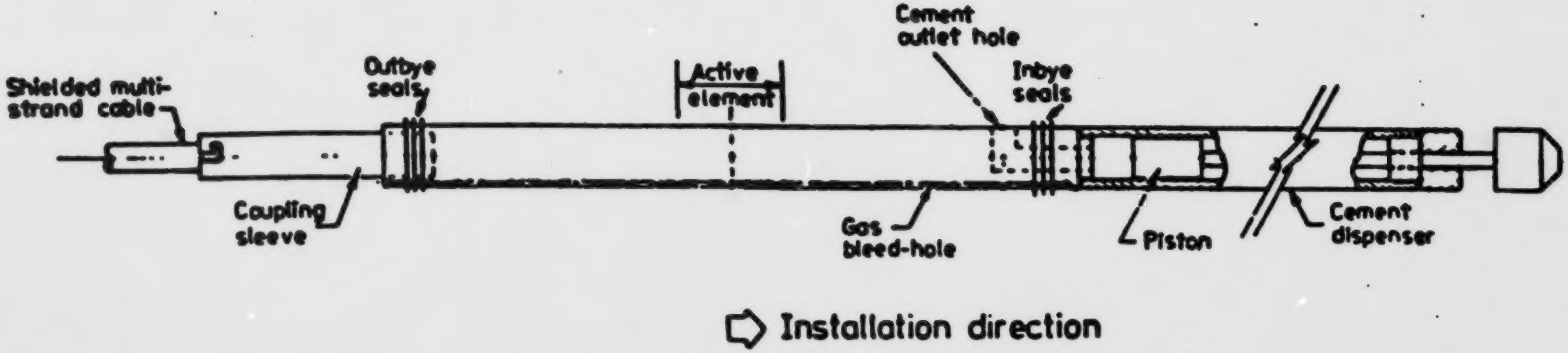

Shielded multi-strand cable
Outbye seals
Active element
Cement outlet hole
Inbye seals
Coupling sleeve
Gas bleed-hole
Piston
Cement dispenser
Installation direction

Figure 15: Solid Soft Inclusion Triaxial Instrument prepared for field use (not to scale).
(Blackwood, 1982)

STRATA

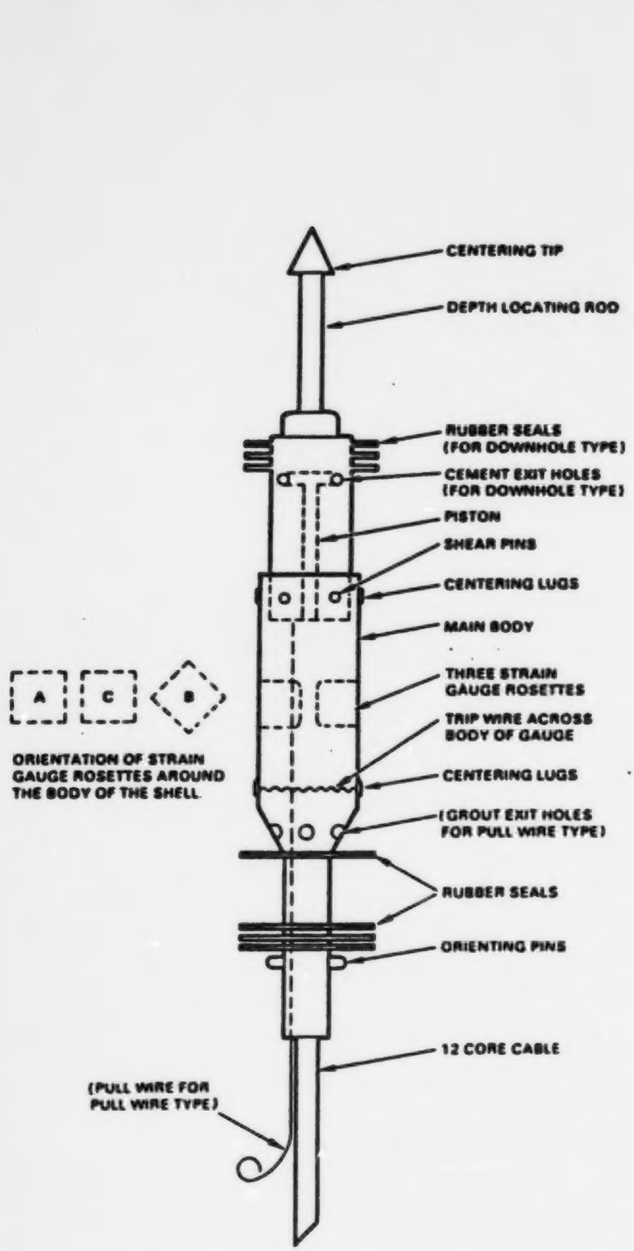

CENTERING TIP
DEPTH LOCATING ROD
RUBBER SEALS (FOR DOWNHOLE TYPE)
CEMENT EXIT HOLES (FOR DOWNHOLE TYPE)
PISTON
SHEAR PINS
CENTERING LUGS
MAIN BODY
A
C
B
ORIENTATION OF STRAIN GAUGE ROSETTES AROUND THE BODY OF THE SHELL
THREE STRAIN GAUGE ROSETTES
TRIP WIRE ACROSS BODY OF GAUGE
CENTERING LUGS
(GROUT EXIT HOLES FOR PULL WIRE TYPE)
RUBBER SEALS
ORIENTING PINS
12 CORE CABLE
(PULL WIRE FOR PULL WIRE TYPE)

Figure 16: Schematic layout of CSIRO hollow inclusion (HI) cell. (ISRM, 1987)

4.3.3.4 Advantages

- determines the complete stress tensor with one test;
- the cell is completely waterproof;
- the cell is monitored throughout the overcoring process;
- very little rock surface preparation is needed in the pilot hole (meaning that the gauge can be installed virtually into any material);
- the integrity of the annulus is assured in most materials because the epoxy used to grout the gauge may also hold the core together.

4.3.3.5 Disadvantages

- the gauge is non-reuseable;
- installation time for the gauge is very long (up to 16 hours);
- the instrument is fairly expensive;
- the epoxy/rock interface can debond during overcoring due to the creation of large tensile stresses (however, there is much controvery over whether this occurs in practice);
- often, the epoxy grout can become plastic, and yield during overcoring. This can be caused by high in situ temperatures or frictional heat generated by the drill bit. If the grout softens sufficiently, the cell behaves as if it were a longitudinally unrestrained cylinder (Irvin et al., 1987).

Laboratory experiments have shown that the CSIRO hollow inclusion cell can expand longitudinally by 50 - 60 microstrains per degree celsius rise in temperature when unrestrained (Irvin et al., 1987).
Radial expansion of the cell is limited to an amount proportional to the relaxation accompanying overcoring, thermal expansion of the rock annulus, and the volume of softened grout extruded from the annulus (Irvin et al., 1987).

Research into the nature of epoxy adhesives revealed two relevant aspects of their behavior (Irvin et al., 1987):

a) high humidity climates adversely affect most epoxy hardeners, in particular those which produce significant exothermic heat. In laboratory experiments, it was found that in high humidity environments, exposed resin surfaces do not set. At high humidities, a hygroscopic reaction takes place, diluting the hardener and preventing set.

b) a different effect is observed in samples cured at low temperatures. The resin sets hard in a reasonable curing time and remains hard as long as the curing temperature is maintained. But, when the temperature is increased, the glue softens and becomes malleable.

During in situ stress measurements in the Donkin tunnel at the Cape Breton coal field, Golder Associates (1983) reported finding a network of bubbles in the glue between the CSIRO gauge and the wall of the pilot hole in deeper tests. They considered the bubbles to be the result of slow groundwater seepage during glue curing. However, there is a good possibility that these bubbles were caused by hygroscopic reaction under a high humidity environment.

4.3.3.6 Applicability

- some experts on overcoring consider this to be the most effective method for coal. Until very recently, this was the only triaxial method that could be used with confidence in coal. Others, however, found this method to be sufficiently lacking in effectiveness that they developed new methods specifically for use in soft rocks. Such is the case with the ANZSI gauge from New Zealand (Mills and Pender, 1986).
- the problem associated with using the CSIRO cell in coal is that the modulus of the epoxy inclusion is relatively high compared to the modulus of coal. Therefore, large tensile stresses are induced in a radial direction at the rock/instrument interface during stress relief (Duncan-Fama and Pender, 1980).

Tensile stresses on the order of 800 kPa were generated when the CSIRO Hollow Inclusion cell was used in coal (Depledge et al., 1980). These stresses were sufficient to cause tensile failure of the epoxy/rock interface and even of the rock itself. This effect however, has been disputed. Blackwood (1982) has spent much time experimenting with the solid soft inclusion cell and has reported that even in highly stressed weak coal, bond failure did not occur. In further laboratory studies, Blackwood concluded that, "...the solid inclusion stress cell can be used in weak rocks with confidence, since the bond stress does not appear to be sufficient to cause the bond to fail in tension." (Blackwood et al., 1986). Therefore, tensile failure may not be a limitation of the epoxy grouted cells, as initially believed;

- Blackwood (1977) has reported great success when using the solid soft inclusion instrument in coal. He states that the integrity of the annulus is assured, in virtually any material, by cementing the complete instrument into the borehole, and that no surface preparation is needed. Therefore, from Blackwood's work, it appears that this instrument may be applicable to coal;

- in practice in Canada, the CSIRO cell has met with only moderate success. Of the five CSIRO tests Golder Associatess tried at the Donkin mine, only two were successful (Golder Associates, 1983). Similarly, of the 28 CSIRO tests that AECL attempted early in its geotechnical program, at the Underground Research Laboratory (URL) in Pinawa, Manitoba, none were successful. Subsequent laboratory testing of various epoxies and installation procedures still did not produce a successful CSIRO test. Eventually this instrument was abandoned at the URL and it was concluded that the CSIRO cell does not work at ambient rock temperatures of 8 ° C, by using recommended or other available epoxies (Thompson et al., 1986). Similar problems with the CSIRO cell in cool, near-surface rocks have been experienced previously (Garritty et al., 1985).

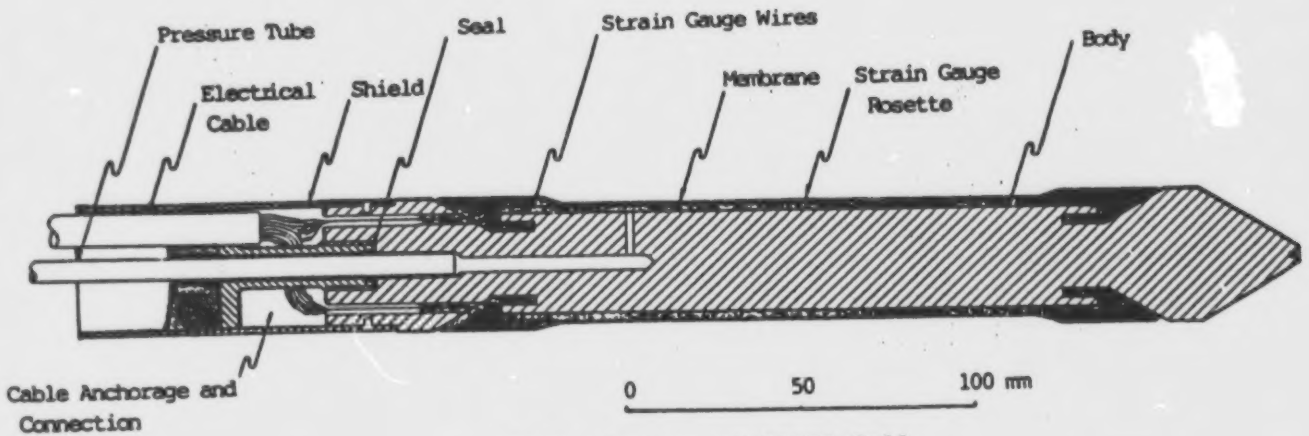
4.3.4 ANZSI (Auckland New Zealand Soft Inclusion Cell) gauge

The ANZSI triaxial stress cell was developed specifically for stress measurements in soft rocks (Mills and Pender, 1986). It is an inflatable soft inclusion strain measuring instrument. Electrical resistance strain gauges are located on the outer membrane surface and are directly bonded to the wall of a 38 mm diameter pilot hole. The relatively low modulus of the ANZSI cell ensures that large, radial tensile stresses are not developed at the instrument/rock interface during stress relief. This greatly reduces the possibility of instrument debonding from the rock, or tensile failure of the rock itself adjacent to the interface. This type of failure is suggested to happen frequently, especially when overcoring in soft rocks such as coal. Figure 17 shows a cross-section of the ANZSI cell and Appendix A contains manufacturers information on this gauge.

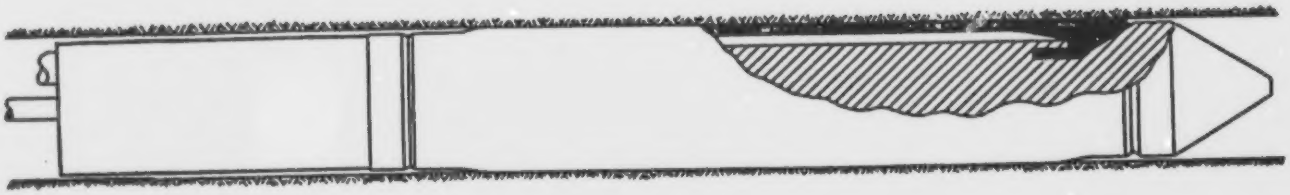
Although the ANZSI gauge was developed mainly to overcome the high tensile stresses generated during overcoring in coal with conventional epoxy grouted instruments, its utilization of the pressuremeter principle offers several other benefits. The main benefit is that an in situ pressure test can be conducted before overcoring. This provides information on whether the strain gauges are operating correctly. It also provides valuable information on rock properties. This is distinctly advantageous, especially if the overcore test is successful, but the core breaks upon removal.

4.3.4.1 Advantages

- the complete stress tensor can be found from one borehole;
- no large tensile stresses are developed at the instrument/rock interface, thereby resolving one of the larger problems of other epoxy grouted instruments;
- strains can be monitored during overcoring;
- the instrument can be used in weak rocks such as coal because it acts to bond the rock together thereby allowing a solid rock annulus to be obtained.


Pressure Tube
Electrical Cable
Shield
Seal
Strain Gauge Wires
Membrane
Strain Gauge Rosette
Body
Cable Anchorage and Connection
0
50
100 mm

Cross-Section of ANZSI Cell



Inflated in Borehole

Figure 17: ANZSI Cell - Cross-Section and Inflated in a Borehole. (Mills and Pender, 1986)

However, it was reported that,... "In coal, intact core suitable for testing is seldom recovered, so that even if the overcoring test is successful, it is often not possible to verify correct operation of each strain gauge without the pressure test." (Mills and Pender, 1986);

- a pressure test can be conducted before overcoring to verify correct gauge operation and to provide information on rock properties.

4.3.4.2 Disadvantages

- some further development of the instrument is considered warranted to improve cement performance, strain gauge contact pressure, and reliability of waterproofing the strain gauge wires (Mills and Pender, 1986);
- the instrument is very new and has not been used very extensively;
- the instrument, although used successfully in coal, has not been used successfully in rocks such as soft mudstones. The strain gauges did not bond because of smear zone formation on the periphery of the hole during drilling (Mills and Pender, 1986). It is suggested that improvements be made in either the cement performance or the drilling technique, or both, to overcome this deficiency;
- excessive methane gas pressures can deflate the instrument and prevent satisfactory bonding.

4.3.4.3 Applicability

- the instrument was developed for use in coal and has been somewhat successful. However, it has not yet been proven extensively enough under various conditions.
- the instrument has not yet been used successfully in weak coal measures strata such as mudstone.

4.4 Hydraulic Fracturing

The hydraulic fracturing method (Haimson, 1978; Zobak and Pollard, 1978) makes it possible to estimate stresses in rock at considerable depths using boreholes. Water is pumped into a section of the borehole isolated by packers. As the water pressure increases, the initial compressive stresses in the borehole are reduced and at some point become tensile. Eventually, a crack is formed and, if pumping is continued, the crack will extend and eventually the pressure will fall to steady state (often called the shut-in pressure). To interpret the data, the orientation of the hydraulically induced fracture must be known. This is determined by using down-hole photography, television cameras, or impression packers. Figure 18 shows a schematic representation of the hydrofracturing tool and impression packer. Figure 19 shows an idealized hydraulic fracturing pressure record.

4.4.1 Advantages

- can be used at any depth or borehole orientation;
- low cost;
- applicable in virtually any type of rock or conditions.

4.4.2 Disadvantages

- hydrofracturing has uncertainties associated with data interpretation (Mizuta et al., 1987);
- some rock types are very difficult to fracture (Golder Associates, 1986).

4.4.3 Applicability

Although applicable in theory, there are problems associated with using hydrofracturing techniques in coal and weak coal measures;

- mudstone, being very plastic, may not be fractured (Golder Associates, 1986). Therefore breakdown pressure may not be achieved;
- when hydrofracturing coal, a very low indistinct pressure peak is obtained because of the presence of existing fractures (Golder Associates, 1986).

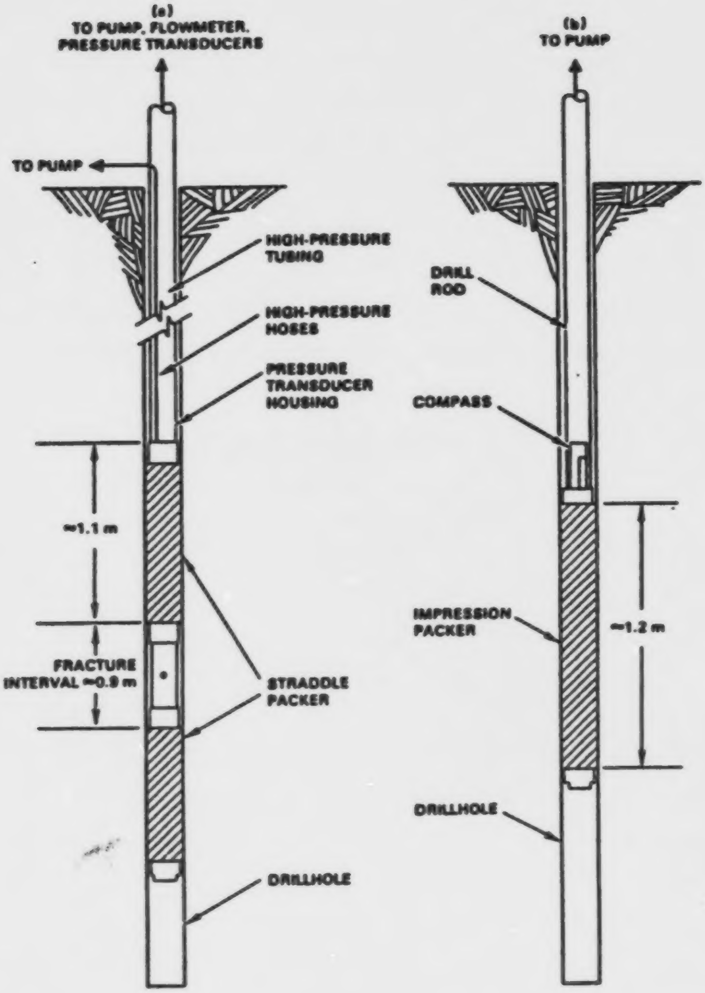

(a)
TO PUMP, FLOWMETER,
PRESSURE TRANSDUCERS
TO PUMP
HIGH-PRESSURE TUBING
HIGH-PRESSURE HOSES
PRESSURE TRANSDUCER HOUSING
~1.1 m
FRACTURE INTERVAL ~0.9 m
STRADDLE PACKER
DRILLHOLE
(b)
TO PUMP
DRILL ROD
COMPASS
IMPRESSION PACKER
~1.2 m
DRILLHOLE

Figure 18: Schematic representation of (a) hydrofracturing tool and (b) impression packer. (ISRM, 1987)

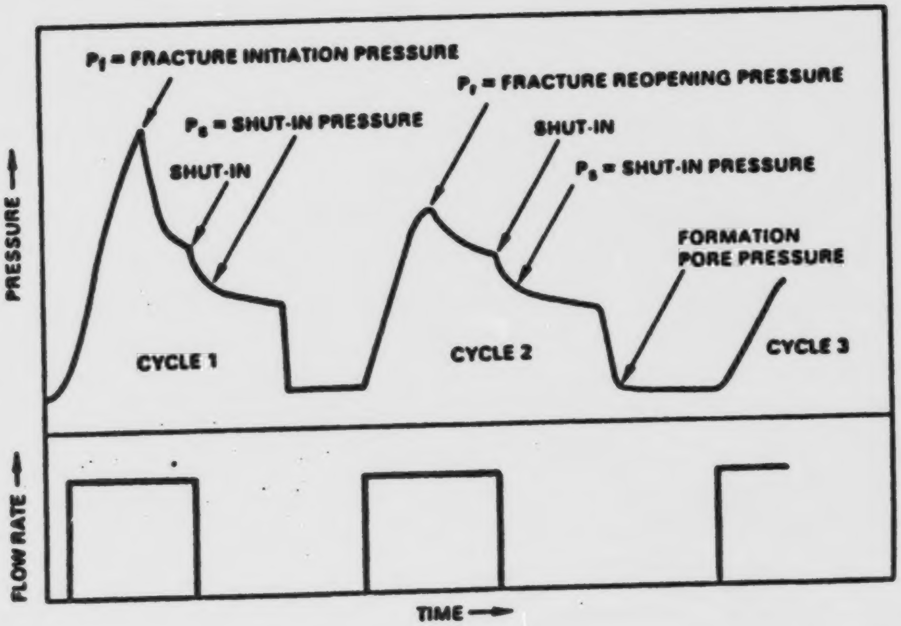

P_f = FRACTURE INITIATION PRESSURE
P_s = SHUT-IN PRESSURE
SHUT-IN
P_r = FRACTURE REOPENING PRESSURE
SHUT-IN
P_s = SHUT-IN PRESSURE
FORMATION PORE PRESSURE
PRESSURE ⟶
CYCLE 1
CYCLE 2
CYCLE 3
FLOW RATE ⟶
TIME ⟶

Figure 19: Idealized hydraulic fracturing pressure record.
(ISRM, 1987)

In the in situ testing program at the Sydney Coalfield (Golder Associates, 1986), breakdown pressure often could not be achieved. This could be caused by leakage out of the test zone through primary permeability, leakage of the rods, and by the lack of availability of compressed air pressure.

4.5 The Flat Jack Method

If access to a rock face is available, stresses can be measured by the flat jack method (Tincelin, 1952). This technique involves cutting a slot into the rock, then installing a flat jack and measuring the amount of pressure required to return the rock to its original state. Figure 20 shows a schematic of the flat jack test.

4.5.1 Advantages

- very inexpensive;
- equipment is very rugged.

4.5.2 Disadvantages

- only one component of the stress tensor is measured in one test. Slots must be made at various angles to obtain the complete stress tensor;
- the measured stress lies in the region of disturbance.

4.5.3 Applicability

- although this method can be used in coal and weak coal measures strata, it does not reveal the natural in situ stress regime without using very complicated numerical methods of analyses. Therefore, it is not very well suited to obtaining the complete in situ natural stress tensor.

4.6 Other Gauges and Methods

There are some alternative gauges that may be applicable for use in coal measures strata. These gauges are relatively untested however and should be extensively studied prior to acceptance for field testing.

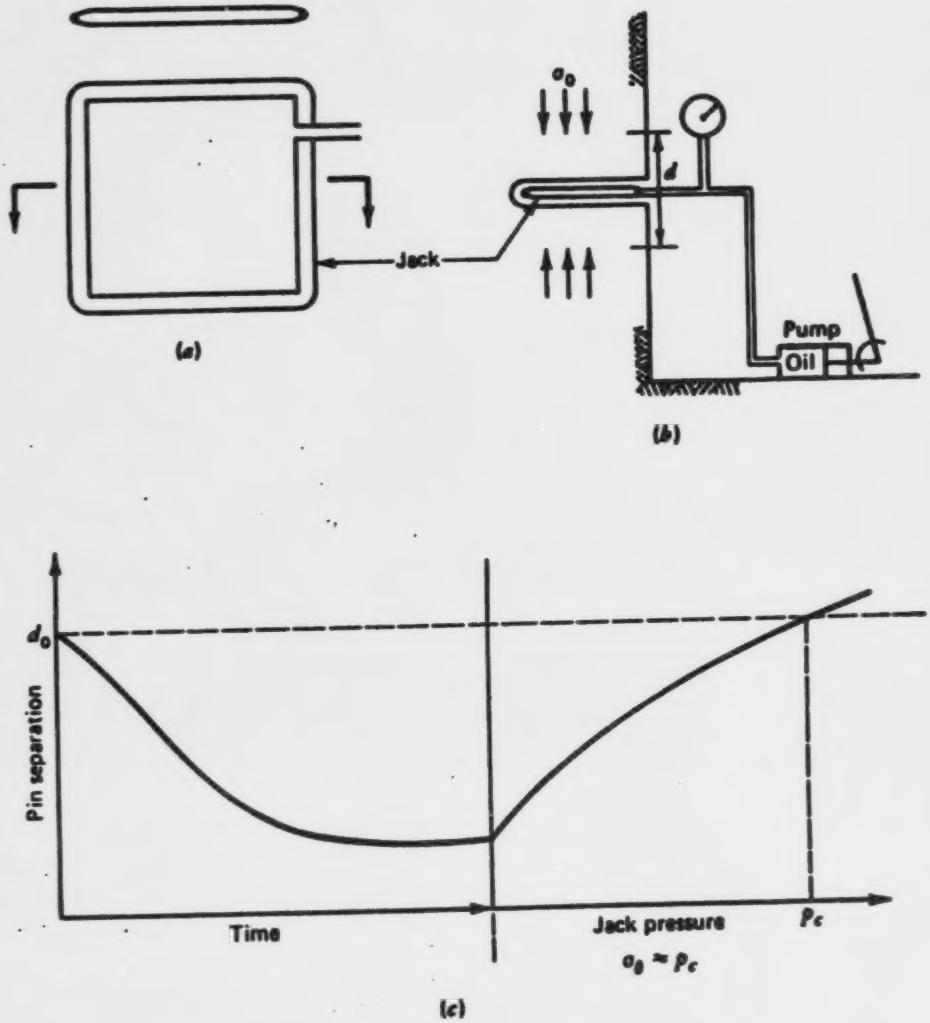

σ0
d
Jack
Pump
Oil
(a)
(b)
d0
Pin separation
Time
Jack pressure
pc
σθ ≈ pc
(c)

Figure 20: The flat jack test.
(Goodman, 1980)

4.6.1 Cast photoelastic inclusions

This method of stress measurement (Riley et al., 1977) uses epoxy resin to fill the EX pilot hole (i.e. no intrument is used). The hole is then overcored and the retrieved annulus is cut into slices. The stress relieved epoxy inclusion can be analysed for stresses in two dimensions using the theory for biaxial photoelastic strain gauges. Although this method has been successfully used in laboratory tests and some field tests, it has not yet become an accepted stress determination method.

4.6.1.1 Advantages

- the method is simple and inexpensive;

- no electrical wires or light sources are needed in the borehole;

- should be applicable at any depth;

- can be used in poor rock because the epoxy will act as reinforcement to bind the entire length of core into an integral piece.

4.6.1.2 Disadvantages

- moisture conditions may cause difficulties for the setting of the epoxy;

- may not be applicable in extreme temperatures;

- the resolution of the method may not be good enough for some purposes.

4.6.1.3 Applicability

- this method should work well provided that the epoxy chosen sets in the acidic, humid environment typical in coal mines.

- as far as it is known, this method has not been tested in coal measures strata; thus, extensive testing of this method would be required.

4.6.2 Holographic in situ stress measurements

This is a new method for measuring the in situ measurement of stress in boreholes (Bass et al., 1986). The instrument operates on the principle of locally relieving the stresses acting on a rock mass by drilling a small hole into the borehole surface and recording the resultant displacement by holographic interferometry. The entire displacement field can be obtained with this method. Figures 21 and 22 show the methodology and a cross-section of the stress meter.

4.6.2.1 Advantages

- the instrument may be used in any type of rock;

- a borehole only is needed for the test (ie. a diamond drill is not required for the stress measurement test).

4.6.2.2 Disadvantages

- the method is not yet proven;

- the present prototype model requires a 30 cm diameter borehole;

- the method is not yet totally adapted to horizontal boreholes;

- the isotropic elastic moduli of the rock must be known.

4.6.2.3 Applicability

Although this method may be suitable for coal and weak coal measures strata, it is basically an unproven method that is still in the developmental stages.

4.6.3 Hemispherical ended borehole technique

This method (Sugawara et al., 1986) is similar to the "doorstopper" technique. The "doorstopper" technique requires two boreholes to determine the complete stress tensor whereas this technique requires only one by reforming the bottom to a hemispherical shape. The method may be applicable to longwall mining.

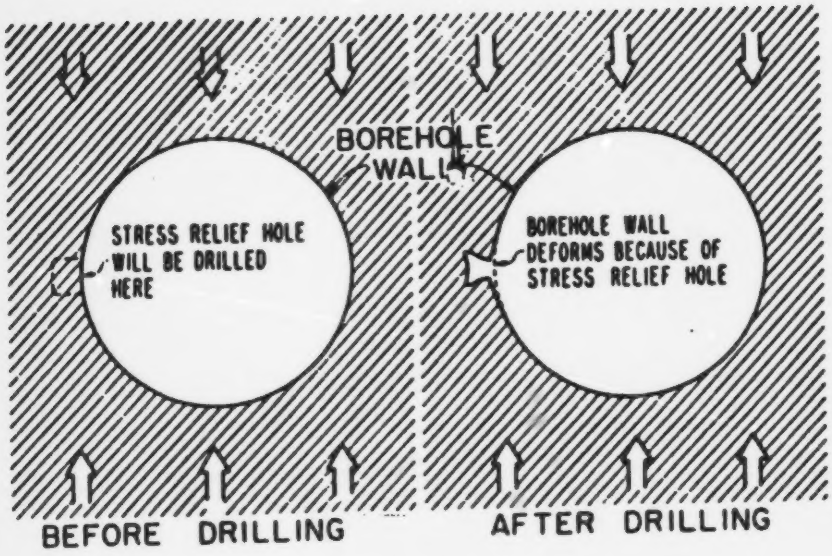

BOREHOLE WALL
STRESS RELIEF HOLE WILL BE DRILLED HERE
BOREHOLE WALL DEFORMS BECAUSE OF STRESS RELIEF HOLE
BEFORE DRILLING
AFTER DRILLING

Figure 21: Cross-section of a borehole under far-field uniaxial stress, illustrating the stress-relief method employed to measure stress. On the left, the borehole surface is undisturbed. A cylindrical stress-relief hole is drilled into the borehole (right), and the adjacent borehoel surface deforms to a degree that depends upon the stress level. The stressmeter records the displacementfield holographically.
(Bass, et. al., 1986)

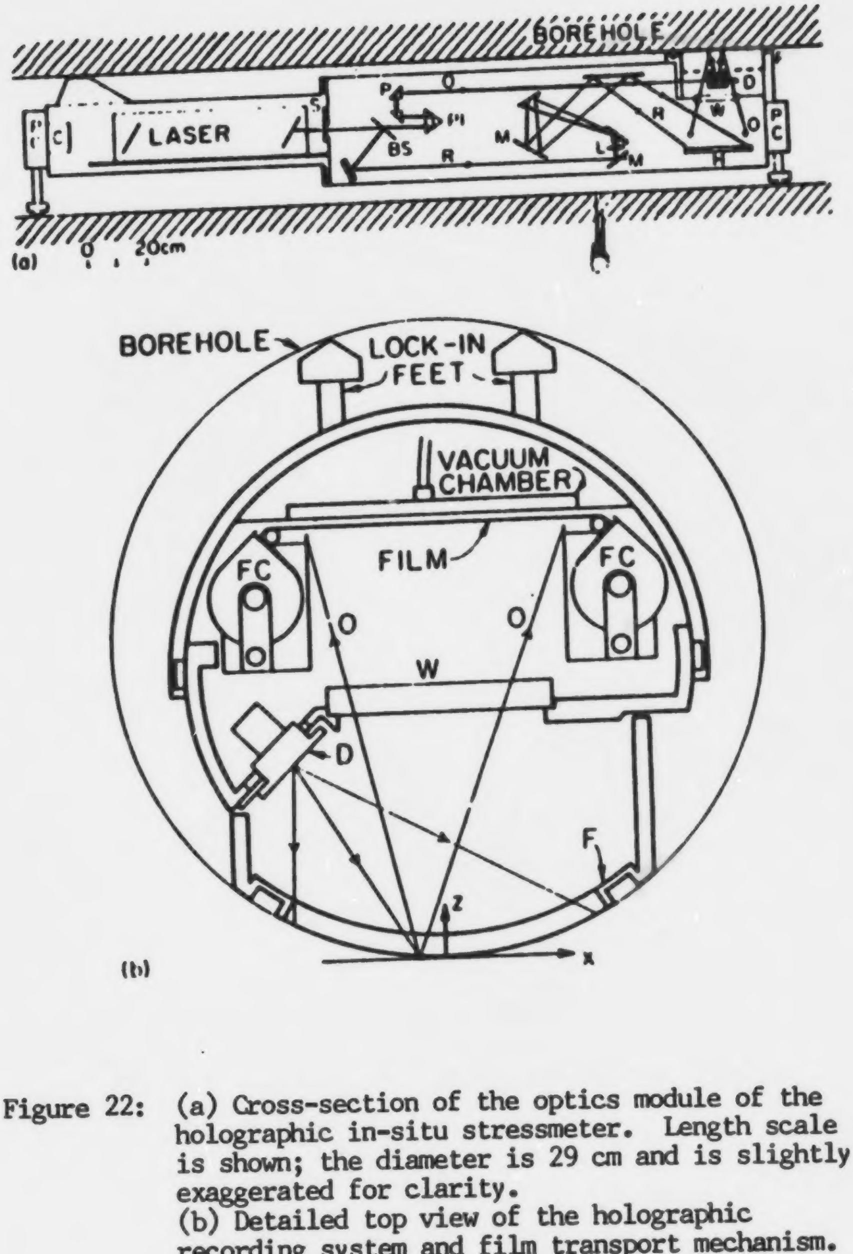

BOREHOLE
C
LASER
S
P
P1
O
BS
R
M
H
L
M
D
W
O
PC
H
(a)
0
20cm
BOREHOLE
LOCK-IN
FEET
VACUUM
CHAMBER
FILM
FC
FC
O
O
W
D
F
z
x
(b)

Figure 22: (a) Cross-section of the optics module of the holographic in-situ stressmeter. Length scale is shown; the diameter is 29 cm and is slightly exaggerated for clarity.
(b) Detailed top view of the holographic recording system and film transport mechanism. Abbreviations: S, shutter; P. P1. prisms; M, mirror; L, lens; R, reference beam; O, object beam; D, diffuser; W, window; H, holographic film plane; C, compass; PC, pneumatic cylinder; BS, beam splitter; F, flange, FC, film cassette.
(Bass, et. al., 1986)

4.6.4 Hydraulic borehole pressure cells

This method (Lu, 1981) determines the magnitude of the biaxial ground pressures existing in a visco-elastic rock mass by pressure convergence tests with a combination of one cylindrical and two flat hydraulic pressure cells installed into a single borehole. Triaxial ground pressures can be measured by drilling a pair of orthogonal holes for instrumentation. Unlike other methods, this technique measures in situ stress without any knowledge of the value of modulus of deformation for the rock. However, in order to determine the complete state of stress existing in a viscoelastic rock mass, other methods are required to determine the directions of principle stresses. This method is thus best suited for measuring changes in in situ stress in coal rather than in measuring the absolute in situ stress field.

5.0 GROUTS

5.1 Overview

Grouting is a procedure in which a bonding or cementing agent (the grout) is introduced, often under pressure, to permeate and fill voids in porous media. The ability of a rock mass to receive grout is called its groutability. The classification of the numerous grouts available today is a difficult problem. The broadest distinction is between "cement" and "chemical" grouts.

Without the benefit of field testing, the groutability of coal must be estimated (or guessed at) from related characteristics, such as permeability.

The comparative ability of grouts to penetrate a rock formation is mainly a function of their viscosities. Penetrability is also related to permeability. A general rule of thumb for penetrability of grouts of various viscosities is shown below :

Grout viscosity (centipoise)	will penetrate formations/materials with permeabilities as low as:
2 cp	10^{-6} m/s
5 cp	10^{-5} m/s
10 cp	10^{-4} m/s

Fracture permeabilities have been measured in coal. A study of coal permeability in the United Kingdom found average values of 10^{-7}m/s vertically and 10^{-4} m/s horizontally (Reddish and Smith, 1982). The fracture opening was estimated to be approximately 0.5 mm. It was determined that the in situ permeability of coal varies greatly due to local fracturing.

5.2 Cement Grouts

Normal Portland cement mixed into a slurry with water will set and bond with other materials, under suitable environmental conditions. Cement-based grouts may be applied to ground comprised of fractured rocks containing enough sizable and continuous voids to facilitate penetration.

Microfine cements were developed for use in materials with smaller voids (i.e. coefficient of permeability of 10^{-5} to 10^{-6} m/s) and have found increasing acceptance over chemical injection agents which are inferior in strength. However, it is doubtful whether microfine cement could adequately penetrate coal fractures without benefit of high pumping pressures.

Cement grouts will not set up in an acidic environment, common in coal mines.

5.3 Chemical Grouts

Chemical grouts (except for epoxies, polyesters and some polyurethanes) have lower strengths than cement grouts. Since cement grouts may not adequately work in coal formations due to the generally acidic environment, chemical grouts are considered a logical alternative for strata reinforcement.

With most chemical grouts, the gel time can be changed by varying the concentration of one or more of the chemical components. Some grouts, after catalyzation, maintain a constant viscosity, and at the completion of the induction period, turn from liquid to solid almost instantaneously. Other grouts increase in viscosity from the moment of catalysis to gel formation.

Gel time is also a function of temperature as well as many other field factors. Of main concern to grouting in coal is the effect of pH and humidity within the host rock mass or formation.

Health and occupational hazards have come under increasing scrutiny in recent times. Thus handling, safety equipment, and toxicity of chemical grouts are also of concern in selection for strata reinforcement purposes.

The characteristics preferred for chemical grout strata reinforcement applications in coal are:

1. Low viscosity - coal formations are not very permeable; low pumping pressures are preferred to minimize alteration of in situ stresses;

2. Waterproof - it is desirable to seal the coal fractures so that water does not seep through them; also, the grout must be able to withstand drilling water pressures;

3. Strength - the coal must be held together during overcoring (to prevent the core from disking), during core retrieval, and during the subsequent biaxial test;

4. Acidic compatibility - coal and possibly coal measures strata are acidic in nature; grouts chosen must set up in an acidic environment;

5. Setting time - a long setting time is preferable in order to allow the coal fractures to relax after being stressed from the grouting process; quick setting grouts will "lock in" stress created by the grout injection pressure;

6. Elasticity - it is preferable to have the grout, after set, either more elastic than or equal to the elasticity of the coal to prevent tensile failure;

7. Safety - the grout must not be unduly hazardous for use in an underground mining environment.

The most widely used chemical grouts are discussed below, along with their applicability to the grouting of coal for strata reinforcement.

5.3.1 Sodium silicate formulations

Gels can be formed from many silica derivatives. The silicate derivatives form the largest single group of chemical grout materials. However, the alkali silicates, in particular sodium silicate, is the only one used to any extent for chemical grouting.

Sodium silicate ($nSiO_2 . Na_2O$) is commercially available as an aqueous solution. The silica/alkali ratio, n, is important in that ranges from 3 to 4 yield gels with adhesive properties suitable for grouting.

When sodium silicate solution and a concentrated solution of appropriate salt are mixed, the reaction forming a gel is virtually instantaneous. The reaction in the formation is expressed as:

$$SiO_2\ Na_2O + CaCl_2 + H_2O\ \text{---}\ Ca(OH)_2 + SiO_2\ 2NaCl$$

Silica is a weak acid and sodium silicate is basic. Silicates are precipitated as a gel by neutralization. However, in an acidic environment (such as in coal), this reaction will not occur. Therefore sodium silicates can not be used in acidic environment coal strata.

5.3.2 Acrylamide grouts

Acrylamide-based materials come closest in terms of performance to meeting the specifications for an ideal grout for coal. They penetrate more readily, maintain constant viscosity during the induction period, have better gel time control and adequate strength for most applications. They are, however, more expensive. Acrylamide is also neurotoxic, and a potential health hazard.

The acrylamide-based grouts consist of a mixture of two organic monomers, acrylamide (about 95% of the mixture) which will polymerize into long molecular chains, and a cross-linking agent such as nethyliene-bis-acrylamide (about 5%), which binds the acrylamide chains together. The elasticity of the grout can be varied by changing the 95:5 ratio.

Uncatalyzed grout solutions have a pH of 4.5 to 5. Catalyzed solutions have a pH of about 8. Gel time control is predicated on maintaining the pH between 8 and 11 (see Figure 23). Higher pH will shorten gel times whereas a pH on the acidic side will lengthen gel times or prohibit gel formation entirely. Thus, acrylamide-based grouts can not be used in acidic environments.

5.3.3 Lignosulfonate grouts

Lignosulfonates are the waste liquor by-products of the wood processing industry. Since the product is not controlled, it is widely variable in composition. Lignosulfonate grouts always consist of lignosulfonates and a hexavalent chromium compound. In an acid environment, the chromium oxidizes with the lignosulfonate to produce a gel. As shown in Figure 24, however, the setting time for this grout is only a few minutes for pH less than 5. Since it is a requirement that the coal be allowed to relax sufficiently after grouting, the fast set time of this grout renders it unsuitable.

5.3.4 Phenoplast grouts

Phenoplast resins are polycondensates resulting from the reaction of a phenol on an aldehyde. Setting time varies significantly with pH, being shortest for any grout pH above 9. Most phenoplasts will not set up in an acidic environment, and are therefore not suitable for grouting coal. Resorcinol is a phenoplast that will set up in an acidic environment. However, gel times will be very long and this will result in a significant decrease in the strength of the grout (see Figure 25). Thus, phenoplast grouts have also been determined as not being suitable for coal.

5.3.5 Polyurethane grouts

Polyurethane grout has been used extensively for strata reinforcement of coal mines and is probably the most popular grout for this application around the world. Unfortunately, a characteristic of this grout is that it expands permanently as it sets and this exerts a positive pressure on the strata around it. Although this is a very desirable characteristic for typical

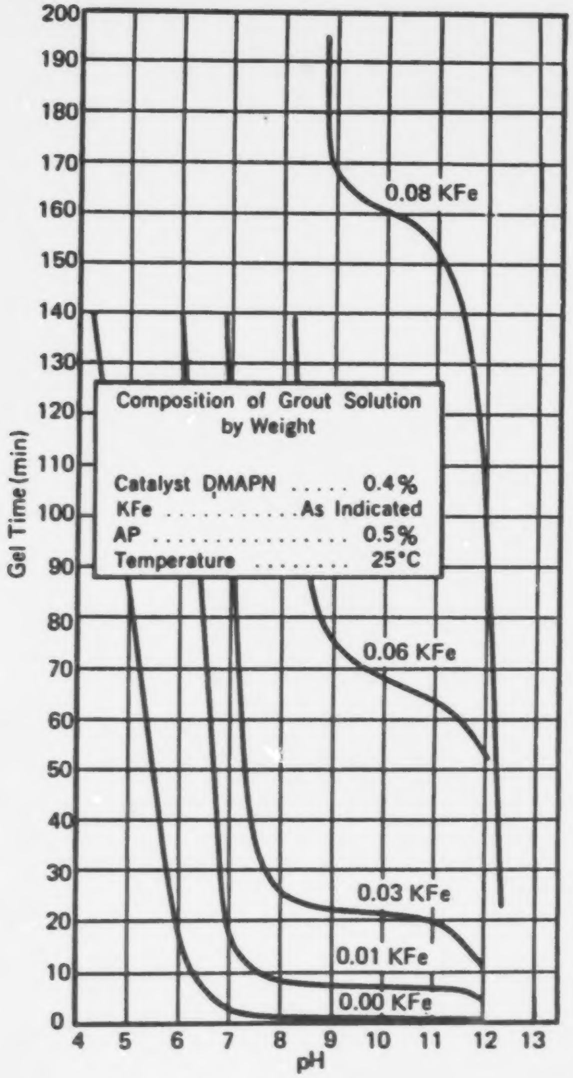


Figure 23: Gel time as affected by pH for Acrylamide-based grout (Karol, 1983)

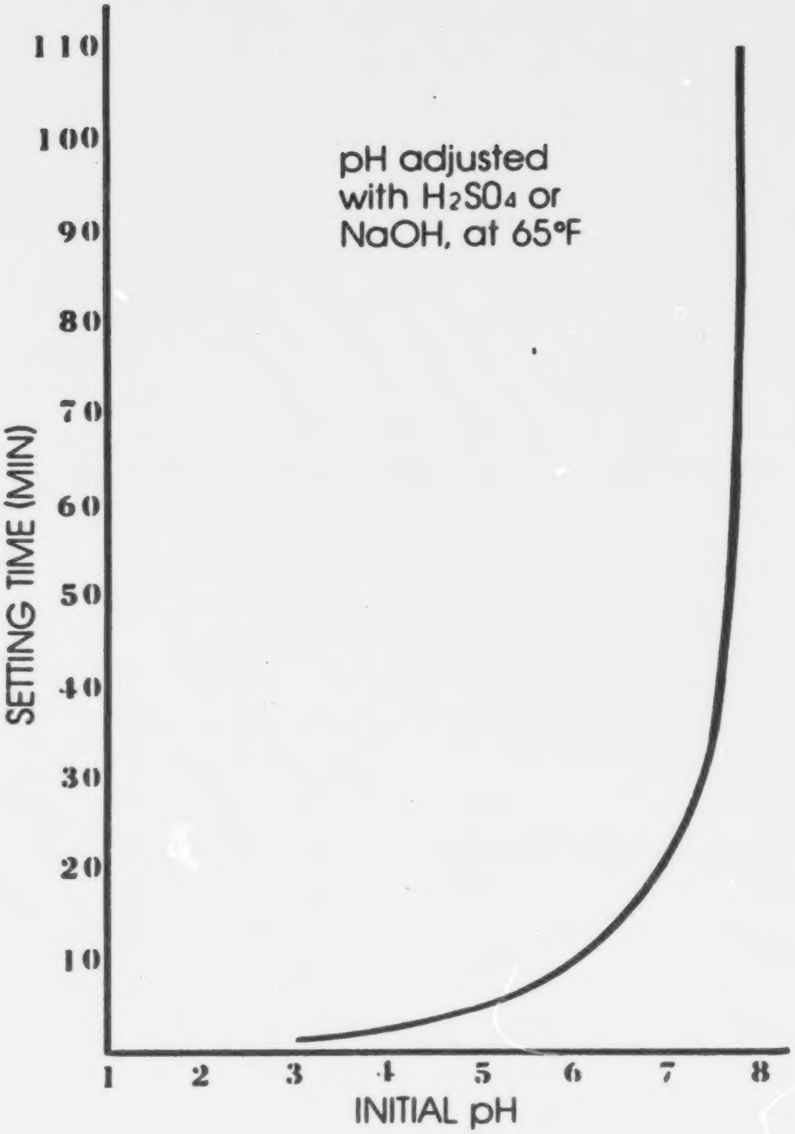


Figure 24 : Effect of pH on setting time of lignosulfonate grouts (pH controlled with H_2SO_4 and NaOH) (Karol, 1983)

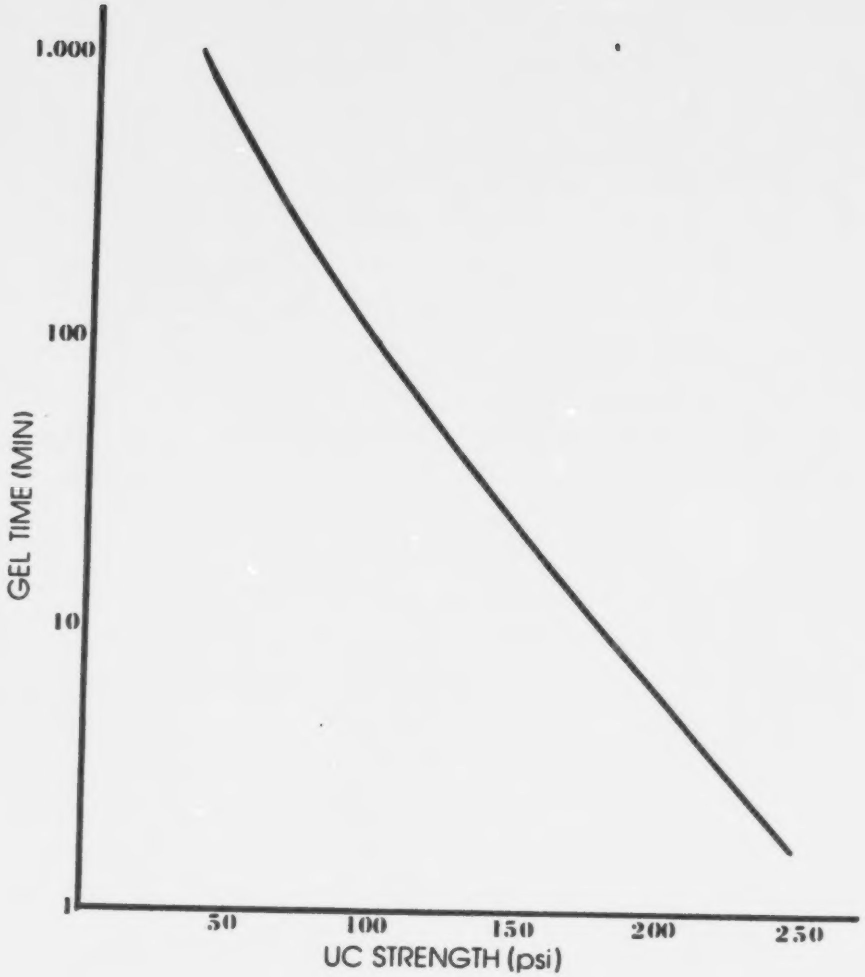


Figure 25: Resorcinol-formaldehyde - setting time versus strength.
(Karol, 1983)

strata reinforcement requirements, it will have a detrimental effect on STROT in that the in situ stress tensor will be altered. This grout may be applicable to STROT if a non-foaming type is developed or if the foaming type can be applied in such a way as to not influence the in situ stress. Therefore, at this time, polyurethane grouts are not being recommended for STROT.

5.3.6 Aminoplast grouts

Aminoplasts are grouts in which the major ingredients are urea and formaldehyde. All urea formaldehyde grouts will set up only under acid conditions and should only be used when it is known that the ground and groundwater pH is below 7 (such as in coal mines).

Urea solutions have very low viscosities, similar to acrylamides and phenoplasts. The reaction with formaldehyde, in addition to requiring elevated temperatures, is rapid and difficult to control. There are intermediate stages in the reaction when the urea is still soluble in water. These materials, called precondensates or prepolymers, are more viscous than the initial urea solution but products can be made that permit the final grout to be used at viscosities in the 5 to 20 cp range. The trade-off in viscosity makes the product easy to handle, with good gel time control.

The prepolymer is a material in which the reaction has been suspended, either by inhibitors, pH control, or both. The reaction continues once the pH is lowered; thus catalysis is usually done with an acid or an acid salt.

Grouts using urea solutions are toxic and corrosive due to the formaldehyde and acid (catalyst) content. Processing using the prepolymer contains much less free formaldehyde than that using the monomer and therefore presents much less of a hazard. The gel, or resin, formed at the conclusion of the reaction, is inert, but it generally contains small amounts of unfixed formaldehyde, which can be a hazard.

Several commercial products are available. One of the grouts is Rocagil AL (Rhone Poulenc, France) which is an aminoplast advertised specifically for use in coal mines. Appendix B contains technical literature on this grout. Cyanaloc 62 (American Cynamid Co.) is a prepolymer marketed as a concentrated liquid which is diluted with water for field use. Sodium bisulfate is the catalyst normally used and the relationship between catalyst concentration and setting time is shown in Figure 26. The gel time is actually the time for formation of a soft gel. Over a few hours or perhaps a day, the gel cures to a harder and stiffer consistency. Cyanaloc, as used for applications requiring strength, will have initial viscosities from 13 to 45 cp, depending on temperature, as shown in Figure 27.

Therefore, it appears that urea formaldehyde grout in the prepolymer form meets the specifications for STROT better than any other grout. For this reason, urea formaldehyde is recommended for STROT.

5.4 Grout Selection Summary

Many different chemical grouts are commercially available. Most require a basic (pH >7) environment for full and rapid development of their properties. Some of these materials (resorcinal and acrylamide) will set up under acid conditions, at a sacrifice of one or more of (a) strength (b) gel time control and/or (c) short gel times.

Portland cement grouts, both normal and microfine, also require a basic hydration environment.

5.4.1 Aminoplast Grout for Coal

Aminoplasts (materials consisting of urea and formaldehyde), require an acid environment for complete reaction, and are the obvious choice for work in coal mines, where both coal and surrounding strata are of low pH.

Figure 28 shows the basic reasoning behind this grout choice.

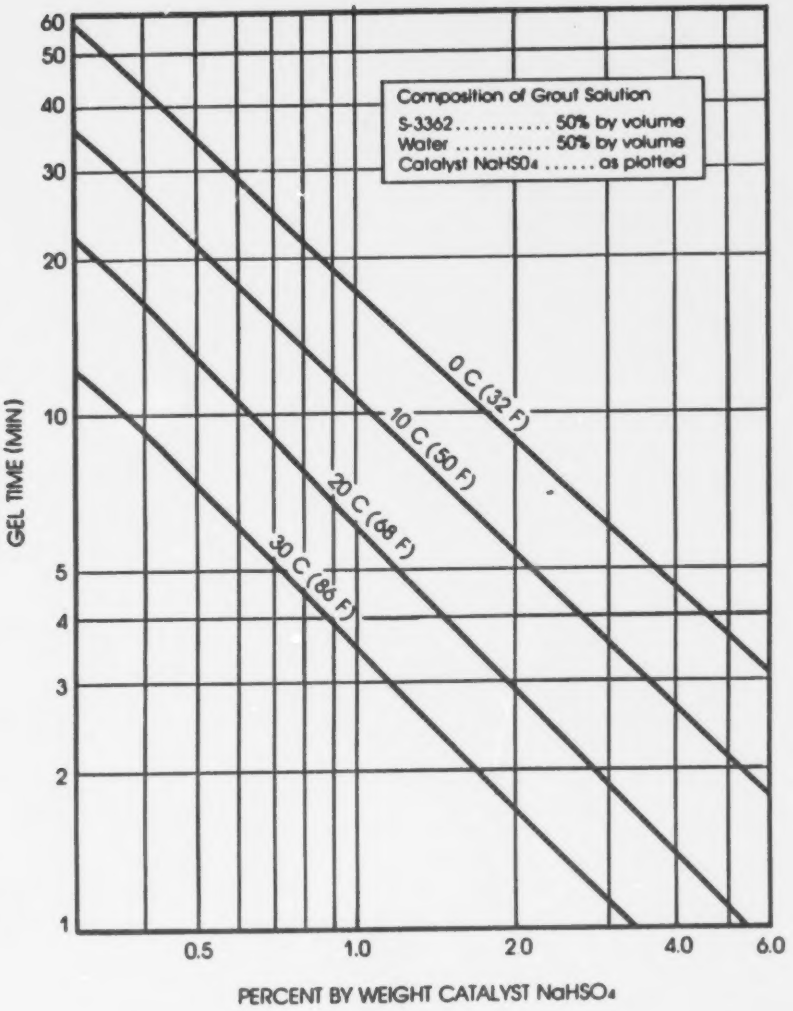


Figure 26: Catalyst concentration versus gel time for urea-formaldehyde grout (Karol, 1983)

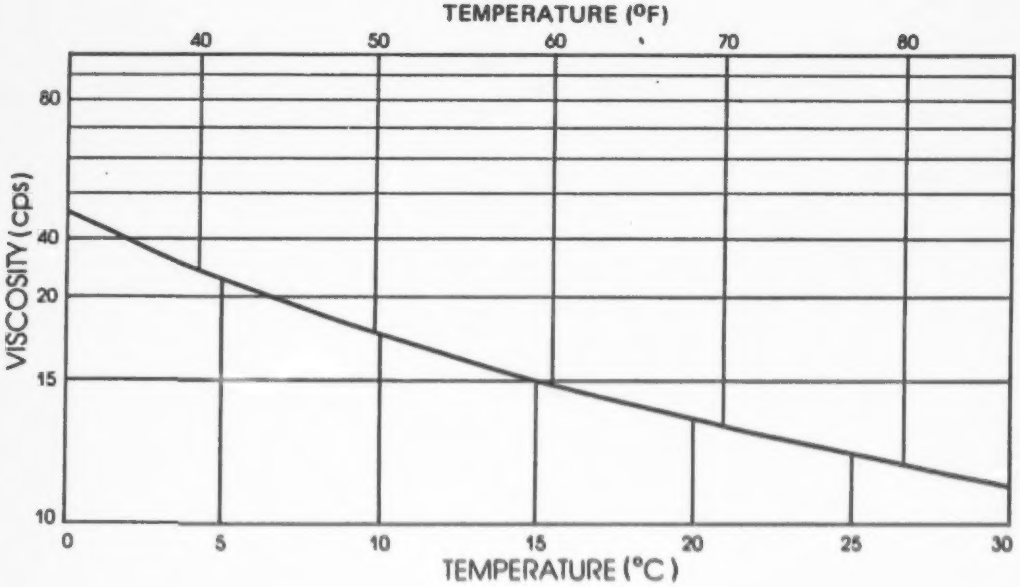


Figure 27: Temperature-viscosity relationship for a catalyzed 50% solution of Cyanaloc 62 urea-formaldehyde grout. (Karol, 1983)

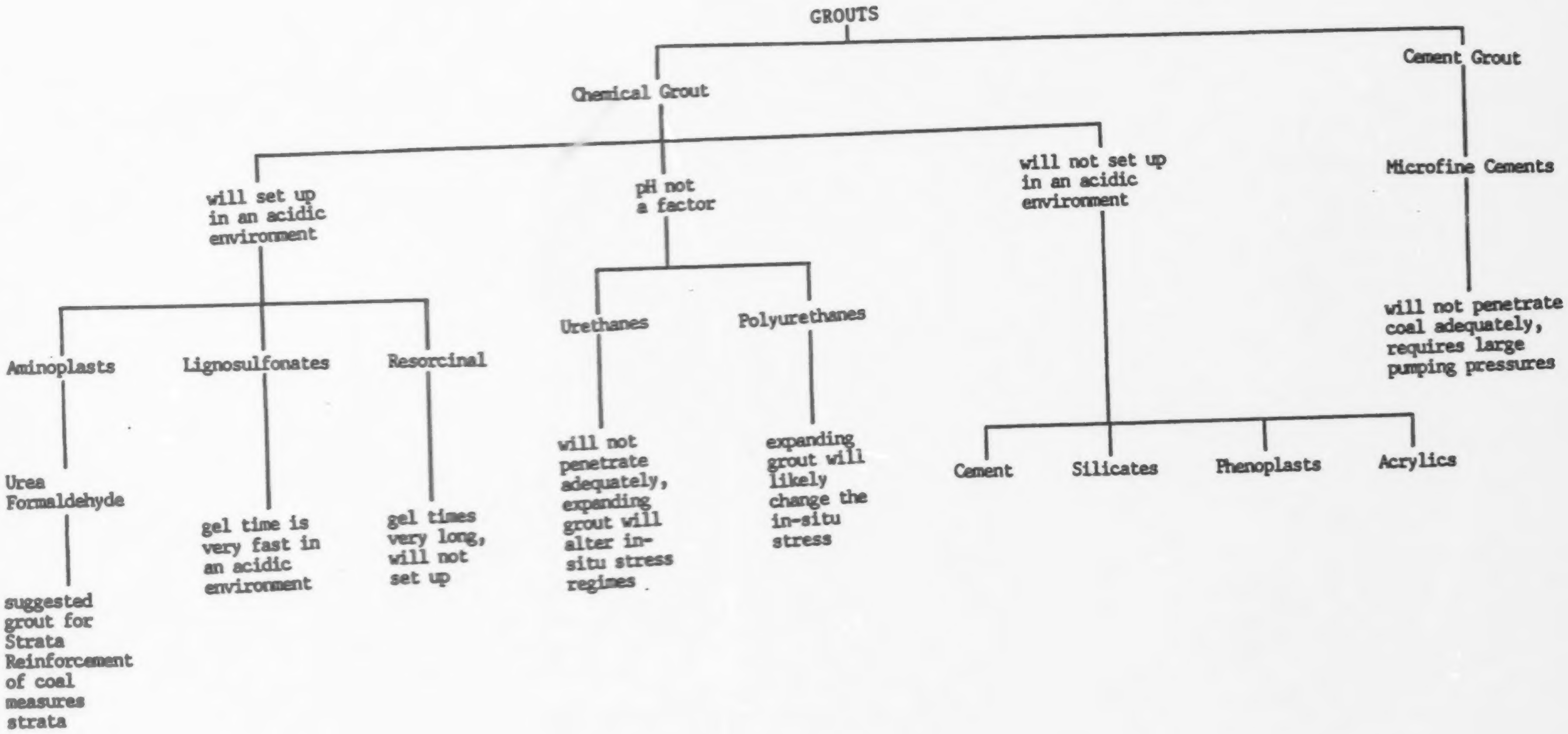

GROUTS
Chemical Grout
Cement Grout
will set up in an acidic environment
pH not a factor
will not set up in an acidic environment
Microfine Cements
Aminoplasts
Lignosulfonates
Resorcinal
Urethanes
Polyurethanes
will not penetrate coal adequately, requires large pumping pressures
Urea Formaldehyde
suggested grout for Strata Reinforcement of coal measures strata
gel time is very fast in an acidic environment
gel times very long, will not set up
will not penetrate adequately, expanding grout will alter in-situ stress regimes
expanding grout will likely change the in-situ stress
Cement
Silicates
Phenoplasts
Acrylics

Figure 28: Suggested Grout for Strata Reinforcement of Coal Measures Strata

A commercial product, Cyanaloc 62, was until recently available in Canada through American Cyanamid. This product may still be available on special order. It is a prepolymer, sold as a concentrated solution which is diluted with water for field use. The catalyst is either an acid or an acid salt.

A French company, Rhone Poulenc, markets a product intended specifically for use in coal mines. This product in liquid form, called Rocagil AL, is available in Canada. The catalyst is a water soluable powder which is available in small quantities. Grout costs will probably be less than $0.50 per litre. Possibly 500 to 1000 litres of grout will be needed for field testing.

5.4.2 Grout Application

The techniques for field grouting are well known to grouting companies, and do not differ much from the procedures used for cement grout. Downhole packers are needed, and special pumping units are required to control grout volume, pressure and setting tme.

In general, pumping pressures should be kept to that minimum value which will permit grout placement at 5 litres/minute or more. Gel times should be adjusted so that the gel forms no sooner than 5 minutes after the pumping pressure is released.

Health hazards are primarily those associated with formaldehyde vapours. Respirators and protective clothing are required, as well as good ventilation facilities. Details are normally available from the grout manufacturer.

In order to keep the pumping pressures low, lower grout viscosities are preferable. However, grout strength varies inversely with viscosity. It is recommended that for the aminoplast type grouts, the viscosity be lower than 10 cp and even lower than 5 cp if adequate strength can be obtained. It is probable that all fractures greater than about 0.05 mm can be grouted throughout the overcore zone. This should reduce the risk of coal breakage or discing but may not eliminate it entirely.

It should be noted that the primary permability of the coal measures is so low that grout penetration with any grouts may not occur. Only the secondary permeability zones, such as cracks and fissures, may be groutable.

Since urea formaldehyde is not reactive with water, it should be able to withstand the rigours of overcore drilling. The grout will remain relatively impermeable and strong as long as it does not dry out. Drying out of the grout will probably not occur until well after the biaxial test and all the necessary information is obtained from the annulus.

5.5 Potential for Altering Strata Properties

One of the major drawbacks of STROT is that the in situ stress regime may be altered. Fractures in coal are tightly closed and grout will not likely penetrate these unless some finite pumping pressure is applied to slightly open these fractures. Unfortunately, there are several problems with this.

First, the forced opening of the fractures will create stresses in a direction normal to the fractures. Short gel time grouts will tend to lock in these induced stresses. However, by using longer gel time grouts at pressures below the elastic limits of coal, the coal may rebound elastically after gel injection so as to close its fractures and return to its natural in situ stress state. Longer gel time is also necessary to allow the excess grout to flow back up the injection lines before setting, as the coal rebounds in time.

The second potential problem is that the fractures may only open in the plane perpendicular to the least principle stress (Σ_3) and the fractures may not be grouted equally in all directions. On the other hand, the grout may penetrate slightly in all directions sufficiently enough to prevent core breakage within the zone of immediate interest. These are potential problems however and can only be confirmed through field tests.

Some concern exists over the effect of the elasticity of the grout on the coal. It is recommended that the grout used be more elastic than the coal in order to prevent tensile failure of the grout upon overcoring. Grouts are not normally designed on the basis of Young's modulus and where knowledge of this elastic property is important, experimental determination is necessary by varying the desired mix parent materials and proportions.

6.0 DISCUSSION

6.1 Measurement of Stresses in Coal

Presently, there are two fundamental problems with applying conventional overcoring techniques to coal;

a) Elastic theory does not strictly apply to coal as a discontinuous material on the scale of a typical overcore test.

b) The overcore test has many practical application problems such as disking of the drill core, debonding of the gauge and the inability to obtain a solid rock annulus for biaxial testing.

The solution to these problems has been suggested by research which has been spearheaded by CANMET involving the use of Strata Reinforcement Techniques (grouting) to stabilize the test area prior to overcoring. This will have several beneficial effects:

a) The joints will be sealed allowing the coal to be modelled as an elastic continuum.

b) The coal will be strengthened, thereby solving the practical problems of overcore drilling (such as disking and recovery of a solid rock annulus for biaxial testing).

6.2 Effect of Grouting on the State of Stress

One of the major drawbacks of STROT is that the in situ stress regime may be altered. This effect could be caused by several factors:

a) high grouting pressure needs for high viscosity grouts;

b) changes in volume during or after grout setting;

c) short setting (gel) times will tend to lock in stresses induced during injection.

In order to alleviate these problems, it is recommended that:

a) low injection pressures should be used for grouting (very low viscosity grouts need to be employed);

b) low volume change grouts must be used; most grouts typically used for strata reinforcement in coal mines are polyurethane based which expand substantially upon setting. These are not suitable for STROT;

c) longer gel time grouts should be used to allow the coal to relax to its natural in situ stress state before the grout sets up;

d) elastic properties of the grout should be compatible with that of coal; a grout much softer than the coal will not substantially strengthen it and a grout much stiffer than the coal will tend to concentrate stresses.

6.3 Strata Reinforcement Overcoring Techniques (STROT)

6.3.1 Normal overcore drilling in coal

The drilling technique used by Blackwood (1982), who reported to have a very good success rate at retrieving a solid coal annulus from overcore testing, is described below.

The overcoring bit used is a stepped crown bit cutting a core of 105 mm, attached to a 165 mm diameter reamer and 1.52 m long thick-walled stationary inner tube core barrel. Although heavy and bulky, it is necessary to use this type of core barrel since it is found that thin-walled trepanning bits and barrels, used successfully in hard rocks, can not form a core in coal. Drilling speeds are kept as low as possible to minimize vibration in order to avoid damaging the core.

An oversize reamer, 165 mm in diameter, is used in conjunction with the bit to give greater than normal clearance around the barrel, since quite significant deformation of the larger hole can be experienced (Blackwood et al., 1976).

Blackwood experienced considerable difficulty in preventing the overcoring bit from drilling eccentrically relative to the pilot hole. This was overcome by installing a close-fitting collar of brass rubbing pads immediately behind the reamer. Because of the necessary close fit of the collar, the overcoring bit and barrel needs to be withdrawn about 150 mm whenever drilling is stopped for any significant period of time, to prevent jamming. Therefore, care has to be taken not to stop drilling during overcoring, as withdrawal could damage any core formed and possibly break the instrument (Blackwood et al., 1976).

The orientation of the borehole is important. Best core recovery in coal is generally obtained when the holes are drilled perpendicular to the main cleat. At all other orientations, there is a tendency for the core to split or for wedges to fall out and jam the barrel (Mills et al., 1986).

6.3.2 Gauge selection

Through literature review, two proven triaxial overcore methods (the solid soft inclusion triaxial cell and the CSIRO cell) and one new method (ANZSI gauge), were found to be potentially useful in coal and weak coal measures strata. All of these methods involve the use of epoxy to grout the gauge into the pilot hole. When using these gauges in coal, the grout is supposed to supply the added benefit of holding the rock annulus together during overcoring. Blackwood (1982) reported good success in obtaining a solid rock annulus from his overcore tests. Mills and Pender (1986) recorded moderate success with the ANZSI gauge. The success of Blackwood's method may be entirely due to a superior drilling technique however, and not because his method is better at holding the coal annulus together.

From conversations with other researchers involved in stress measurements, the ANZSI gauge is recommended for use in coal. Although Blackwood's solid soft inclusion gauge may also work in coal, it has not been extensively used by others and generally does not appear to be an accepted method.

The CSIRO cell is not being recommended because it may create high tensile stresses between the coal and the cell which could result in instrument/rock debonding during overcoring.

Although the ANZSI gauge may supply all the necessary elastic information about the coal prior to overcoring, it is still desirable to obtain a solid rock annulus so that the rock properties may be determined in a biaxial test and the correct gauge operation may be confirmed. In closely jointed coal, such as at the Sydney coalfield, the chances of obtaining intact cores are low. In addition to this, a problem exists whereby slight water seepage into the pilot hole during epoxy curing could "wash out" the epoxy thereby impairing the rock/instrument bond.

These problems of obtaining a solid rock annulus for laboratory testing and of achieving a good rock/instrument bond could be solved with the use of strata reinforcement overcoring techniques (STROT).

6.3.3 STROT Methodology

Two methodologies for strata reinforcement appear feasible and it is recommended that both be tested in the field.

6.3.3.1 Central Grout Hole Method (C G H-STROT)

Although the central grout hole is likely the least expensive and fastest method of STROT, it may be susceptible to large errors. The error arises from the inelastic redistribution of stresses in the immediate vicinity of the rock mass in which the stresses are to be measured. This inelastic deformation is anticipated because the hole for grouting is drilled in a discontinuous medium (jointed coal). However, it is recommended that this method be checked in the field because the error created may not be large compared to the typical errors encountered during overcore drilling.

Details of CGH-STROT are as follows:

- drill an HQ size borehole to the desired depth and flatten its end;

- using a core bit smaller than the EWG size pilot borehole (ie. less than 35 mm O.D.), drill an initial hole (grout hole) into the centre of the bottom of the HQ size borehole to the full depth of the intended overcore (typically 500 mm). Such core bits may not be available commercially, but it is presumed they could be manufactured [Longyear Canada - Personal Communication].

- grout the entire length of the small diameter grout hole with an aminoplast grout at low pressure.

- after the grout has set, drill the regulation size EWG pilot borehole. This will remove all the grout from the inside of the pilot hole and leave only coal and grouted fractures in the core annulus;

- perform a normal overcore test using the ANZSI and/or the USBM gauge.

6.3.3.2 Radial Grout Hole Method (R G H-STROT)

The radial grout hole method will not produce the same errors as the central grout hole method because the coal may be more correctly modelled as an elastic continuus mass before the pilot hole is drilled for overcore testing.

Details of RGH-STROT are as follows:

- drill several boreholes in the proposed test area within a 1 m radius of the test hole location. The number of radial boreholes required will depend upon the groutability of the coal at the test location;

- grout the radially drilled holes, to achieve a fully grouted zone in the overcore test area through overlapping.

- perform a normal overcore test using the ANZSI and/or the USBM gauge.

6.3.4 Benefits of STROT

The improvements created by STROT over normal overcoring methods are anticipated to be as follows:

- the coal may be modelled using linear elastic continuum theory;

- the core annulus becomes much stronger and therefore the chances of obtaining a solid core annulus are much greater;

- water seepage into the borehole is reduced ensuring a good bond between the instrument and rock, since any fractures would be grout-sealed prior to installation of the instrument;

- incidents of instrument short circuiting by water will be reduced;

Although STROT may prove to be considerably more expensive than standard overcoring techniques, it should pay for itself with a higher percentage of successful overcore tests and with less loss of equipment and/or data.

The deployment of STROT at the Sydney coalfield will require an extensive program of preparatory, laboratory and field research and perhaps development, to evaluate the various factors and techniques involved in a successful application of either the CGH or the RGH STROT methodologies. Details of a proposed R & D program are given and discussed in the next section of this report.

7.0 PROPOSED R&D PROGRAM FOR STROT

7.1 Linear Phased vs. Multiple-Stream R & D Approaches

As discussed earlier in this report, it would be beneficial to develop a strata reinforcement overcoring technique (STROT) for stress measurements directly in coal. To this end, it is proposed that a program of research and development (R & D) be undertaken, under the surveillance and guidance of the Cape Breton Coal Research Laboratory, CANMET, to demonstrate the effectiveness, viability, and efficiency of STROT. This section of the report describes potential R & D projects for implementation in a phased manner, to ensure effective control of finite resources and funds which might be allocated to such an R & D program over a one to three year period.

A linear phased R & D approach is best suited for this purpose, as it allows better control of expenditures. The linear approach permits the Scientific Authority to exercise tighter control on decisions to continue or terminate a project. On the other hand, a multiple-stream R & D approach, where several sub-projects are run in parallel, requires much greater coordination and monitoring by the Scientific Authority, and greater effort to reconcile and collate the various R & D efforts into one cohesive entity for evaluation of its overall effectiveness.

The linear phased R & D approach is illustrated in Figure 29. It has been designed specifically for STROT, and ensures full control by the Scientific Authority. It permits termination of the R & D program, at any stage, without serious loss of data or knowledge acquired up to the time of termination of the project. Its logic is predicated on a methodical approach to STROT investigation.

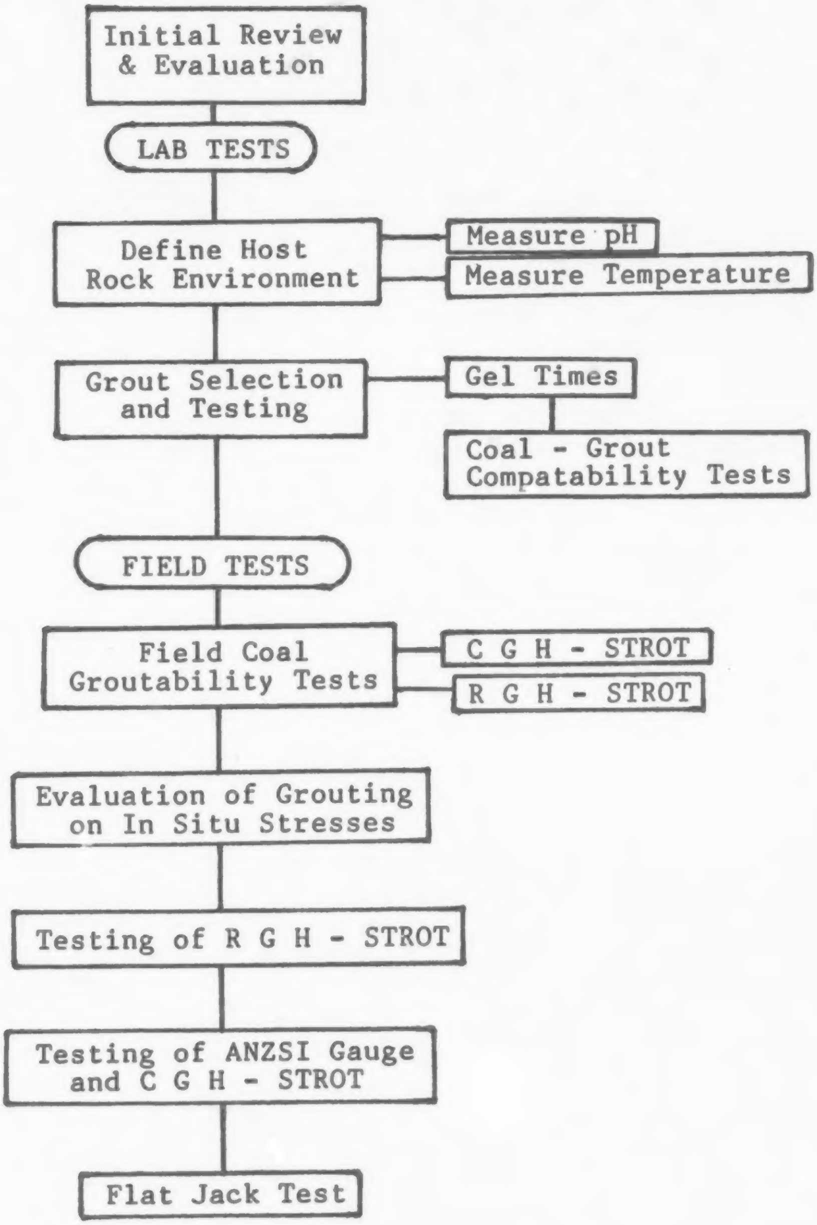

Initial Review & Evaluation
LAB TESTS
Define Host Rock Environment
Measure pH
Measure Temperature
Grout Selection and Testing
Gel Times
Coal - Grout Compatability Tests
FIELD TESTS
Field Coal Groutability Tests
C G H - STROT
R G H - STROT
Evaluation of Grouting on In Situ Stresses
Testing of R G H - STROT
Testing of ANZSI Gauge and C G H - STROT
Flat Jack Test

Figure 29. Flow chart showing linear phased R & D approach for development of STROT

7.2 R & D Phasing for STROT

The linear phased R & D program requires a step-by-step approach to the problem at hand. One starts with the obvious, by planning and conducting statistically valid laboratory and field experiments to yield maximum information at least possible cost for the greatest benefit. One then progresses in a linear fashion to the next phase if the results of the previous phase are satisfactory. If problems have arisen in the previous phase, then one might consider a limited-scope multiple-stream minor R & D thrust to resolve such side issues, whilst maintaining the main thrust linearly towards the ultimate goal.

The linear phased R & D approach suggests the obvious place to start is to define the host rock environment in which STROT is to be applied.

7.2 .1 Host Rock Environment

The use of chemical grouts and the design of an appropriate grout mix requires reliable knowledge of the environmental conditions prevailing in the area of interest. The two most important environmental factors for STROT application are temperature and pH of the host rock. Low grout viscosities best achieve greater and more complete penetration into the coal mass. However, low viscosities usually result in low post-set grout strengths. Since viscosities and set times are temperature dependent, and since grout choice is pH dependent, a knowledge of both temperature and pH of the host coal and coal measures strata is critical to the optimization of chemical grout reinforcement design for use in STROT.

Therefore, the first phase of any STROT R & D program should be dedicated to the measurement of temperatures and pH in the host rock environment.

7.2.1.1 pH determinations

The pH of the coal at the Sydney coalfield has been previously determined, by others (Aston, 1988, personal communication), for processing purposes after extraction. The pH was determined by mixing coal fines with water and allowing the slurry to stand for 24 hrs. By such measurements, the pH of the Prince Mine coal is approximately 2 to 2.5 whereas that of the Lingan Mine coal is 4 to 5.

Coal fines have a much greater surface area per unit volume than coarser or intact coal. Hence, the pH measurements after 24 hr. soaking may represent an extreme value. It would be valuable to repeat such pH measurements using coal fragments of different gradations, and for different soaking times, at different temperatures, in different soaking media, and either covered or uncovered to determine the influence of gas entrapment or escape on pH values.

A potential experimental matrix for the determination of pH values would consist of the following variables:

(1) Coal Gradation: 50 - 25 mm, 9.0 - 4.75 mm (#4 sieve), 180 - 250 µm (#30 to #60 sieve size) and Fines (±75µm), for a total of four minimum variables;

(2) Slurry Media: Sea Water, Tap Water, Distilled Water, Urea, and an acrylamide base, for a total of five minimum variables;

(3) Standing Time (Hrs): 0.5, 2.0, 6.0, 12.0, 24.0, for a total of five minimum variables;

(4) Temperatures (°C): 10-15, 20-25, 30-35, for a total of three minimum variables;

(5) Gas Tightness: Covered after mixing and uncovered, for two variables per combinations of (1) to (4) above.

Each of these variables can then be subjected to an analysis of variance for tests of statistical significance.

Since the type of pH probe can be an important factor in pH determinations, two different types (eg. standard and an alternate) could also be introduced as an additional variable in the experimental matrix for pH determinations.

It is well known from the field of water chemistry that pH determinations are subject to wide fluctuations depending on a number of factors, including immediacy of measurement, as well as many of the variables listed above. Of those listed, the most difficult to control will be gas tightness. Unless special container cover devices can be manufactured or are readily available to allow introduction of the pH meter probe into the slurry without allowing escape of gases, only one set of readings will be possible on any given slurry mix. Therefore many replicate samples might be required. Hence, coal samples for pH testing should be prepared to ensure statistical validity.

All of these pH experiments can be conducted in a controlled laboratory environment. Field tests (see Section 7.2.3, this report) using the same probes will also be necessary in the various parts of the test section of the host rock, in conjunction with in situ temperature measurements, to determine the in situ host rock environment.

7.2.1.2 Temperature measurements

At present, the coal mine in situ rock temperature is not known precisely. The in situ temperature probably ranges between 15 and 25 °C. The host rock temperature must be known more accurately as it is critical to the choice of grout and epoxy mixtures, as well as grout set times.

Large temperature differentials between drill water and host rock may cause thermal fracturing (by "quenching"), especially in winter work if the supply water is near freezing, and the temperature at the drill bit face in the host rock is approaching 100 °C or greater. Therefore, temperature effects are of significance from this point of view also.

In situ temperatures can be measured by a variety of methods. Each method and its precision range is shown below (Considine, 1974):

Method	**Precision**	**Cost**
Thermocouples	± 1° C	Least
Thermistors	± 0.5° C	
RTD's	± 0.1° C	Most

RTD's (Resistance Temperature Devices) are the most reliable of the three, and are also the most expensive. They are justified for purely scientific research where precision of measurement is important. Thermistor costs can approach those of RTD's if calibrated units are desired for direct temperature comparisons between various units. Experience indicates thermistors should always be duplicated so that if one fails in a pair, the other can still provide data.

For purposes of STROT, T-type (copper-constantan) thermocouples will probably suffice. Their junctions may be joined by routine silver soldering using a borax flux, or a soft solder using a resin flux.

The installation of thermocouple junctions is important for reliable measurements of temperature. Conduction errors can be reduced by ensuring tight contact between lead wires to the junction and the surrounding host rock. The junction should also be inserted deep enough into the medium in which the temperature is to be measured.

Therefore, a simple program of field trials will be necessary to construct thermocouples, and to calibrate the junctions before insertion. It is recommended that the thermocouples be inserted into boreholes near the proposed area for in situ stress measurement testing. The downhole temperatures should be monitored over a period of time to establish the equilibrium time requirements for that type of installation.

7.2.2 Grout Selection

Critical factors in grout selection have been discussed earlier in the report. The most important of these for STROT applications are penetrability, gel or set time, and post-set strength. Penetrability will be a function of viscosity at time of injection, and pressures used. All of these requirements are, however, inter-dependent. Therefore, the object of this phase of the R & D program should be to optimize the gel time for maximum grouted strength of the coal at the lowest possible viscosity of the grout injected under the least necessary pressure.

7.2.2.1 Gel times / viscosity

Commercially available grouts come with manufacturer's specifications as to viscosity and gel times which, for an R & D program, must be verified. Customized grouts mixed on site for specific use will need to be similarly tested for routine property evaluations. For applications in coal, it will also be necessary to establish both a field and a laboratory testing program to optimize the mix design of the selected grout.

In the laboratory, the temperature-viscosity behaviour of a grout can be easily determined in standard viscometers, for various mix proportions, and at different induction temperatures.

Next, the variables of (1) coal type, (2) coal size, and (3) coal-grout mix temperatures can be introduced into the experiment. Since coarse coal-grout mixtures can not be evaluated by standard viscometer devices, it may be necessary to construct an apparatus similar to the asphalt needle penetration device, or to modify one of these, to obtain data on viscosities and gel times for the various coal-grout mixtures and temperatures.

An important variable in this labortory experimental matrix will be the moisture content of the coal, and its pH. It may therefore be necessary to run a series of tests on coal soaked for a period of time in the native mine water, and then allowed to dry to different moisture contents before being placed in the coal-grout mix batch for viscosity and gel time observations.

7.2.2.2 Coal-Grout compatability

It is important that the grout and coal exhibit physical and chemical compatability. The testing of the compatability criteria will involve a series of laboratory and field experiments.

For laboratory evaluations, triaxial tests should be performed on several native cores of coal to determine the elastic properties of the unreinforced samples. Initially unreinforced (i.e. ungrouted or native) core samples should be tested to some safe pressure below failure, sufficient for the determination of the unreinforced elastic modulus. While still in the triaxial cell, the samples should then be reinforced by grouting with the selected grout type. After grout-set, the triaxial test should be continued to determine the elastic properties of the grout reinforced sample.

It is important to test the same core sample before and after grouting for statistical and scientific validity. This phase of work may require modifications to standard triaxial test cells for the introduction of the grout, and for determination of grout set-time under the prevailing cell test pressure. A number of core samples should be tested to obtain likely values of the standard deviation of the elasticity modulus.

Such laboratory tests will provide valuable information on the feasibility of STROT prior to field overcoring trials, and yield initial information on the groutability of the coal.

Upon completion of test, the core samples can be cut open and examined and tested for grout take, and other index properties of the grouted coal (eg. relative density, unit weight, final moisture content, etc.).

7.2.3 Field Applications

It is important to recognize the significance of the preceding phases of research in ensuring effective utilization of available research dollars and effort towards the realization of STROT for in situ stress determination in coal and weak coal measures strata. Field STROT trials conducted with or without benefit of the foregoing R & D phases can have only two possible outcomes - success or failure. Neither can be explained rationally without benefit of the information generated by the types of R & D work proposed earlier in this section; but both can be rationalized with the proposed background R & D work.

However, and more importantly, the risks of failure can be substantially reduced for any contemplated field trials using the linear R & D approach, as one could pre-determine the choices available for field trials before they are conducted. If conservation of time and resources is a priority, then clearly the linear phased R & D approach is best suited for this type of work, where an extensive literature survey (this study) shows little or no precedence to permit proceeding on a multiple-stream R & D basis with any degree of confidence or justification.

It is therefore recommended that field trials be confined to later phases of the R & D program, until some preliminary laboratory and field work has been completed.

Figure 30 illustrates a typical test face within the coal mine and the possible location of specific tests proposed for the field testing phase of the R & D program. The establishment of such a test face should be the responsibility of the Scientific Authority, having due regard for access, safety, representativeness of the coal in the area, and requirements for in situ stress information in the test area.

Such a test area can then serve a multiple of field experimentation needs for STROT verification and utility.

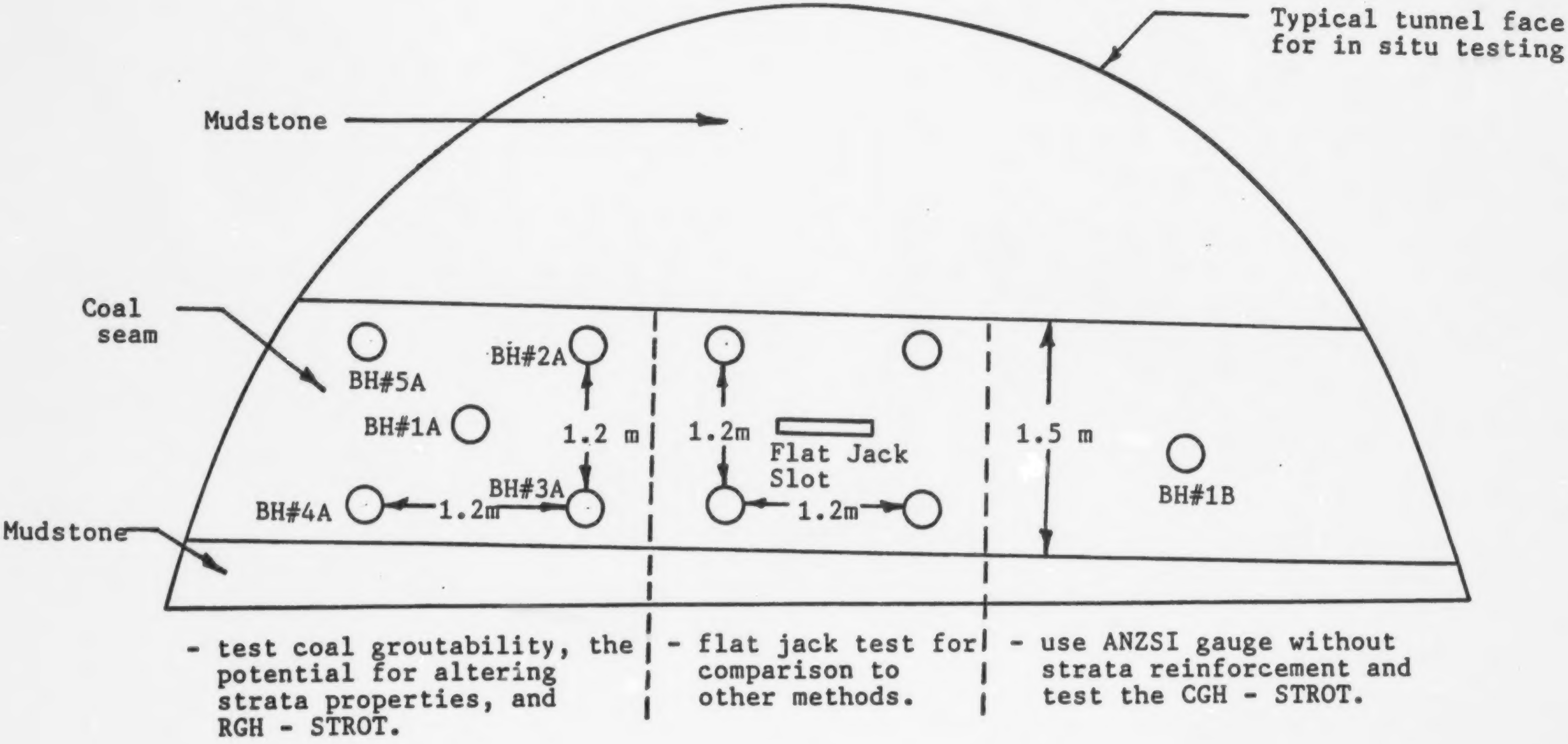

Typical tunnel face
for in situ testing
Mudstone
Coal
seam
Mudstone
BH#5A
BH#2A
BH#1A
1.2 m
1.2m
Flat Jack
Slot
1.5 m
BH#1B
BH#4A
1.2m
BH#3A
1.2m
- test coal groutability, the potential for altering strata properties, and RGH - STROT.
- flat jack test for comparison to other methods.
- use ANZSI gauge without strata reinforcement and test the CGH - STROT.

Figure 30. Proposed layout of in situ field tests for R&D program.

7.2.3.1 Field Coal Groutability - C G H STROT

The effectiveness of the central grout hole (CGH STROT) method can be determined by drilling and coring hole 1A (Figure 30) to a depth of about 3 m into the face and injecting grout at as low a pressure as possible, within an acceptable range of pre-determined grout take values. The injection pressure and grout take rate should be monitored. After grout-set, four holes (2A, 3A, 4A, 5A) should be drilled to determine, by core recovery, the penetration distance of the grout. These holes will also indicate whether or not the grout injection has improved core recovery, as previous control data on ungrouted core recoveries is likely already available. If such control native coal core recovery data is not already available, it might be worthwhile to core drill another part of the test area face to establish the core drilling control parameters (rate of penetration, drill pressure, water pressure, cutting speed, type of core barrel, type of core bit discharge, etc.) and also to obtain the average core recoveries. The same drill core control parameters should be used in coring holes 1A and the other four holes after the grouting of hole 1A.

7.2.3.2 Field Coal Groutability - R G H STROT

The viability of the radial grout hole (RGH STROT) method can be established upon completion of the CGH test drilling.

Holes (2A, 3A, 4A, 5A) should be extended from the 3 m to the 6 m depth. Grout should then be injected, in the same manner as with hole 1A in the preceding CGH trial. After grout-set, hole 1A should be core drilled to determine the core recovery and to check on the grout spread, overlap and penetrability.

These two tests simulate the two methods of STROT being recommended and will also determine the groutability of the coal and whether or not core recovery can be substantially improved with grouting. The results of the tests can be used to determine the future direction of the development of STROT.

If necessary, more tests can be performed at greater depths, in the same boreholes, in order to perfect the grout injection process and core drilling techniques.

7.2.4 Evaluation of grout reinforcement on in situ stresses

Tests will be required to determine whether or not the in situ stress regime has been affected by grout reinforcment, as practiced in the CGH and RGH methods, described in the previous section.

To determine the influence of grouting on in situ stresses, hole 1A (Figure 30) should be extended to at least one tunnel diameter from the face. An ANZSI gauge should then be installed into this hole. Holes 2A, 3A, 4A, and 5A (Figure 30) should then be extended to the test depth and grouted while monitoring the strains measured with the ANZSI gauge. This procedure will indicate whether or not the in situ stress regime has been permanently altered by the grout injection process, and the recovery time for stresses to return to ambient values, should permanent stress change not occur.

7.3 Implementation of STROT

The strata reinforcement overcoring technique, having now been proven and ready for implementation, can then be applied to actual overcoring tests.

To this end, holes 2A, 3A, 4A, and 5A should be extended to a depth of two tunnel diameters from the face. The holes should then be grouted using the techniques established previously. After the grout has set, hole 1A should be extended to the grouted zone (the recovered core will indicate where the grouted coal has been intersected).

ANZSI and USBM overcoring tests should be performed within the grouted zone in a repetitive and consecutive manner. The repetitive ANZSI tests will give confidence in the reliability of in situ stress measurements in coal. The USBM tests can serve as controls on the new and relatively untested ANZSI gauge.

It is also suggested that several ANZSI tests be done beyond the grouted zone to compare overcoring in the continuous medium grouted coal with the discontinuous natural coal rock mass.

7.3.1 Testing of the central grout hole (CGH STROT) method

It is possibile that the CGH-STROT method may produce inaccurate results. The reason for this assessment is that drilling the central hole will affect the stress field in the vicinity of that hole. On the other hand, the RGH method has the advantage of not changing the stresses in the test hole area. Hence, field testing will be required to determine the amount of error in the CGH method. If the central grout hole method does not produce errors that are anticipated, it will be the most economical STROT method to use for future routine field testing.

It is proposed that borehole 1B be extended to the same depth as STROT testing in borehole 1A. Run an ANZSI overcore test to determine the natural in situ stress regime (without strata reinforcement). In situ pressuremeter tests should be completed prior to overcoring to determine the elastic properties of the rock. A normal overcore test should then be carried out. If a solid rock annulus is obtained, then a biaxial test should be done on the core.

The next stress measurement would use strata reinforcement combined with the ANZSI gauge. This test and the ANZSI tests without STROT should then be used alternately down the borehole until consistent results are obtained.

These tests will determine whether the in situ stress regime is significantly altered by either the test methodology or the grout injection, by comparison of the results between the two types of overcore tests. The data can also be compared with the radial grout hole method to determine the optimum technique.

7.3.2 Flat Jack Testing

As an inexpensive back up test to check the overcoring results, it is recommended that two flat jack tests be done in area C (Figure 30). One of these tests will be in ungrouted coal (control) and the other in grouted coal.

These tests will supply information on the natural in situ stress regime by back calculations using numerical methods. It will also give valuable information on the effect of grouting on the in situ stress regime.

7.4 Equipment and Expertise Requirements

For field testing of the STROT, three areas of speciality will be required. These are drilling, stress measurements, and grouting.

It is assumed that all equipment proposed can be made intrinsically safe for use in coal mines. All equipment will have to comply with the statutory requirements of the Coal Mines (CBDC) Safety Regulations and be approved by CANMET.

For drilling, the following expertise/equipment is needed:

- a driller with experience in drilling coal;
- a helper;
- a good electrical hydraulic drill with separate feed rate and speed control (such as an LY38). It is important that the drill produces as little vibration as possible;
- Four types of drill bits are required: an HQ flattening bit, an EX bit, a triple-tube barrel H overcore bit, and a special bit smaller than the EX size.

For stress measurements, the following expertise/equipment is needed:

- a technician experienced in overcoring practices;
- a data logger, preferably one that can read up to 20 separate channels;
- stress measurement gauges and equipment; ANZSI gauge, USBM gauge, flat

jack, installation tools, rods, epoxy, swabs, and cables;

- transducers for obtaining drilling information such as torque, thrust, speed (RPM), rate, and drill stem water pressure;

- thermocouples installed in various locations to monitor the cell temperature, and all inflow-outflow water temperatures.

For grout reinforcement, the following expertise/equipment is required:

- a technician experienced in grouting procedures;
- down hole packer system for grout injection;
- chemical grout metering pump;
- necessary pipes and hoses for grout injection;
- grout, catalyst and water;
- safety equipment such as respirators, gloves, safety glasses, body coverings, etc.

7.5 Applications of Research

The development of STROT will have wide ranging benefits such as:

- the method can be applied to all discontinuous rock and may have applications in mines other than coal mines;

- the data on the grout testing and the triaxial tests can be placed in the CANMET data bank for other research purposes;

- the grouting technique developed may be used for other rock mechanics applications;

- different types of stress measurement cells can be evaluated through this project and in particular the state of the art ANZSI gauge can be evaluated for Canadian coal mining applications.

This research will give CANMET the opportunity to introduce the ANZSI gauge to North America and, if STROT is proven as a viable alternative, CANMET will become a world leader in in situ stress measurements of coal.

8.0 CURRENT AND FUTURE CANADIAN COAL INDUSTRY NEEDS

Canada is well endowed with coal reserves. In Western Canada, the geological reserves of coal have been estimated at over 100 billion tonnes (Latour and Chrismas, 1970), of which about 30 per cent is estimated to be thermal coal and the balance coking coal. In the Appalachian Region of Southeastern Canada, over 450 million tonnes of coal has been extracted since 1880 (Rose et al., 1976). Figure 31 illustrates the location, production and recoverable reserves of the coalfields of Southeastern Canada. This figure clearly shows the predominant position of the Sydney coalfield, which accounts for over 90 per cent of the total estimated reserves in Southeastern Canada.

The Sydney coalfield is located along the northeastern coastline of Cape Breton Island in Nova Scotia. Nearly all of the Sydney reserves lie in the submarine area, and are estimated at over 1 billion tonnes of recoverable resource within an 8 km limit of the Canadian shoreline (Rose et al., 1976). The peak annual production in the Sydney area was reached in 1940 with an output of just over 5 million tonnes.

The three collieries operated by the Cape Breton Development Corporation in the Sydney area are the Prince Colliery at Point Aconi, Lingan Colliery at New Waterford, and the No.26 Colliery (now shut down) at Glace Bay.

As the more profitable coal reserves become depleted, the demand grows on the Canadian coal mining industry and the coal mining geologists and engineers, to render coal mining techniques more productive and economical, whilst maintaining high standards of safety. Such demands require a greater knowledge of the potential behaviour of coal measures strata in the yet unexplored reserve formations. Only through intensive and persistent research can rational and more confident predictions be made of future performance in such new reserves. Past performance can then be a useful guide for the calibration and validation of rational predictive models which such research thrusts can put into the hands of the mining engineer. However,

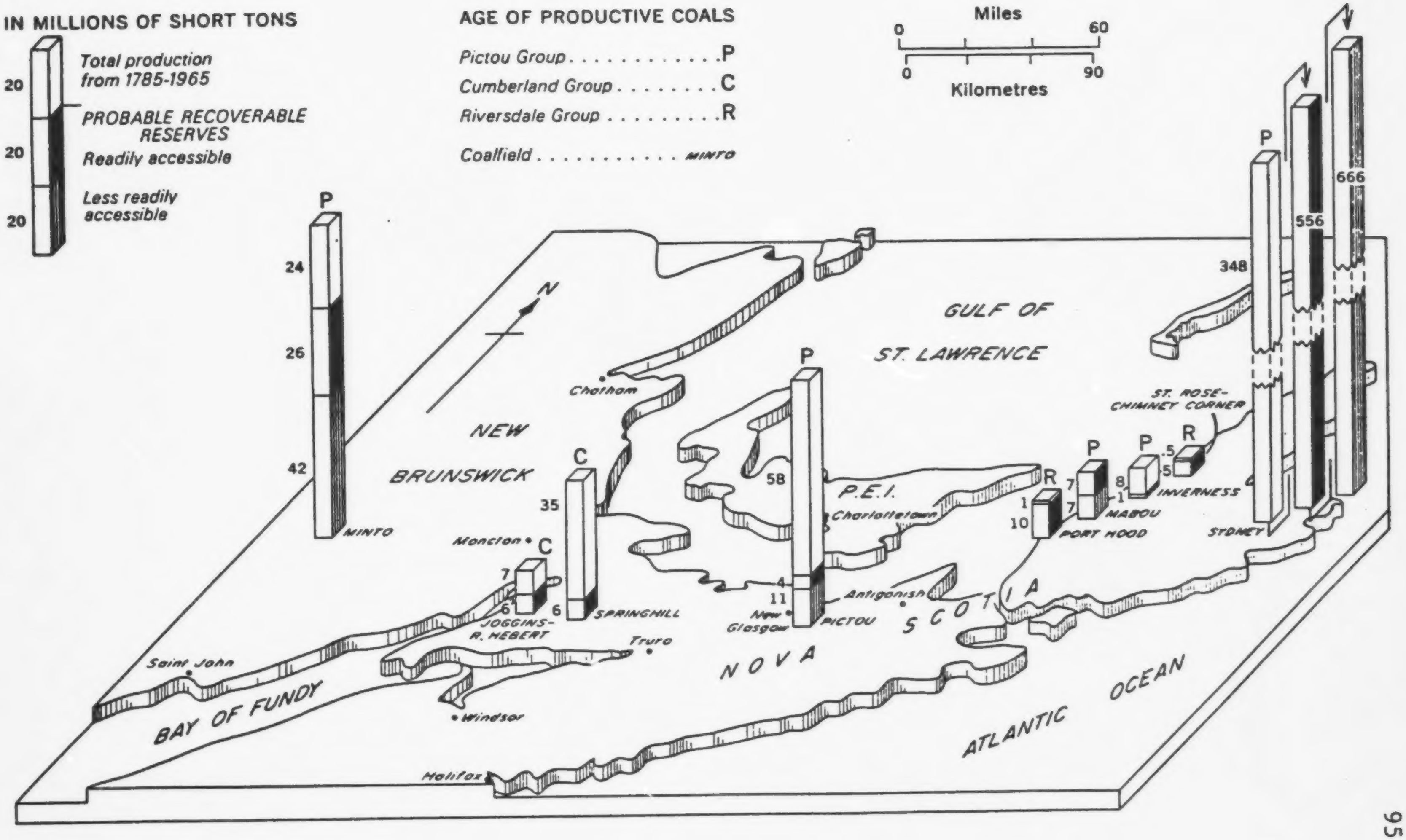

IN MILLIONS OF SHORT TONS
20
20
20
Total production from 1785-1965
PROBABLE RECOVERABLE RESERVES
Readily accessible
Less readily accessible
AGE OF PRODUCTIVE COALS
Pictou Group . . . . .P
Cumberland Group C
Riversdale Group . . . . .R
Coalfield . . . . MINTO
Miles
0
60
0
90
Kilometres
P
24
26
42
MINTO
N
NEW
BRUNSWICK
Chatham
C
35
6
SPRINGHILL
Moncton
C
7
6
JOGGINS-R. HEBERT
Saint John
BAY OF FUNDY
Windsor
Halifax
Truro
P
58
4
11
New Glasgow
PICTOU
Antigonish
P.E.I.
Charlottetown
NOVA SCOTIA
GULF OF ST. LAWRENCE
R
1
10
PORT HOOD
P
7
7
MABOU
P
8
1
R
.5
5
INVERNESS
ST. ROSE-CHIMNEY CORNER
P
348
556
666
SYDNEY
ATLANTIC OCEAN

Figure 31. Location, production, and recoverable reserves of the coalfields of Southeastern Canada (Rose et al., 1976)

such predictive models will be only as good as the field data used. One of the key field data required for modelling and prediction is the nature and magnitude of the in situ stress within the coal itself.

For example, one of the critical factors in the design of tunnels, support systems, pillars and entry intersections is a knowledge of the natural in situ stress regime within the coal. It has been shown that horizontal stresses and geological discontinuities have the greatest influence on intersection stability (Hanna and Conover, 1988). Past experience has also shown that re-orientation of entries oblique to the horizontal principal stress directions is effective in reducing the severity of roof failures at the face and in limiting the height of roof falls after mining (Hanna et al., 1986). In situ stresses also play a significant role in outburst occurrences.

This literature review has shown there is great concern also in other parts of the world with the determination of in situ stresses in coal. Australia and New Zealand are devoting much effort to developing techniques to do so. However, this initial thrust by CANMET/EMR at investigating Strata Reinforcement (STROT) techniques for such measurements is a world FIRST to date, as revealed by this current literature review.

It would appear that Canada, through CANMET and its research facilities and personnel at the Cape Breton Coal Board in Sydney, Nova Scotia, is presently poised to be a co-leader in the field of in situ stress measurements in coal, along with Australia and New Zealand. The ANZSI gauge is being regarded as a state of the art in situ stress measuring device for coal. When successfully combined with strata reinforcement techniques, as the current research thrust would have it, Canada will undoubtedly assume world leadership in this field. STROT has the potential to become the accepted worldwide standard for in situ stress measurement in coal and weak coal measures strata.

The possibilities of technology transfer from further research and development in STROT are very high. This review has indicated the need for some basic information which one might have suspected would be easily available after almost 200 years of "modern" coal mining history world wide. The fact that very little such basic information is available attests to the utility and foresightedness of the current research thrust by CANMET into strata reinforcement technologies. It proves further that experience and judgemental empericism have thus far played a much larger role in coal mining, than have rationally based design decisions. The new order requires more rationalization of design, coupled with past experience, and more use of modern tools, products and technologies, to render the less desirable coal reserves more economically and competetively viable. Technology transfer, therefore, is a vital factor in the development, acquisition, deployment, and dissemination of new knowledge on STROT, starting with some basic fundamental research under CANMET leadership, in areas as outlined earlier in this report.

This review and evaluation has shown the possibility of maintaining and enhancing CANMET's leadership role by means of laboratory and field experiments and trials, ranging from the simple to the more complex. It is recommended that serious consideration be given to implementation of the STROT R & D program, as outlined in Section 7 of this Report. Such an R & D program could be phased, in a linear fashion, perhaps over a one to three year period, to obtain an insight into the many advantages the STROT concept has to offer to the Canadian coal mining industry in particular and to the mining industry worldwide in general.

9.0 CLOSURE

A comprehensive literature survey file has been created to catalogue available data on in situ stress measurement techniques both in general and in specific terms, the latter more related to the mining of coal. The general references deal with chemical grout reinforcement potential and stress measurement by overcoring and other techniques. Specific references deal with the use of cement and chemical grout applications in coal and weak coal measures strata, and overcoring techniques that may be applicable in the post-reinforcement stages.

Contacts with various authorities has been established to ensure that all possible sources of information are being tapped effectively. A listing of contacts established in this literature survey is provided in Appendix C. This list can be used at a future date by others interested in any specific area of applied research relative to in situ stress measurements in coal.

Dr. Tim Aston, Research Scientist, Cape Breton Coal Research Laboratory, CANMET, and Scientific Authority for this project, provided valuable guidance throughout this study. His helpful comments, ideas and encouragement have been a significant factor in our motivation and our efforts. Reflected in this study are the high quality expectations he has set for this research, which we hope we have met by this submission.

Respectfully submitted,
STRATA ENGINEERING CORPORATION

Ed Harvey

Ed Harvey, B.A.Sc.
Project Engineer

Cam Mirza, M.S., P.Eng.
Project Manager

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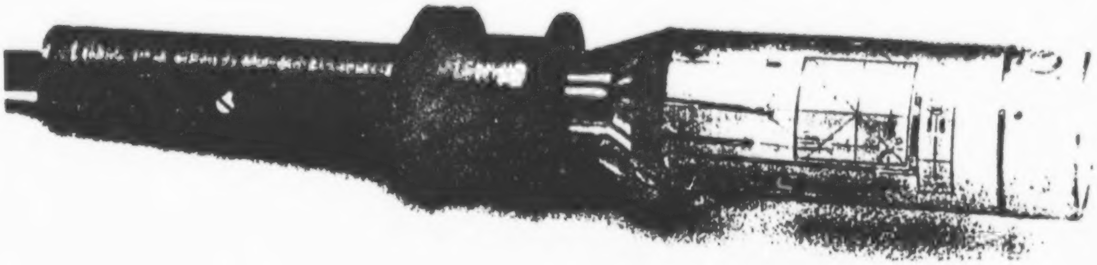
APPENDIX A

Manufacturer's information on overcore gauges

CSIRO* HOLLOW INCLUSION STRESS CELL

A PROVEN INSTRUMENT FOR TRIAXIAL STRESS MEASUREMENT IN ROCK



Since it became commercially available in 1977 the CSIRO HI CELL has proven to be a reliable and accurate instrument for use in conjunction with the borehole overcoring technique for rock stress measurement.

Major Features:

- ★ Determines the complete stress tensor from one measurement
- ★ Permanently attached data cable
- ★ Cell is monitored throughout the overcoring process
- ★ Completely encapsulated electrical resistance strain gauges
- ★ Employs 10 mm long strain gauges to increase the accuracy of measurement in rock with large grain size
- ★ Cell installation without the use of pneumatic or hydraulic equipment
- ★ A range of purpose designed grouts for cell applications over a range of in-situ conditions.
- ★ The hollow construction of the cell significantly reduces the strength of the bond required between the cell and the rock over that required for solid, soft inclusion
- ★ The cell can be left permanently installed in the borehole and used as a triaxial rock stress change monitoring instrument

*Commonwealth Scientific & Industrial Research Organization

Construction:

The HI Cell consists of an array of nine or twelve electrical resistance strain gauges which are encapsulated in the wall of a thin walled epoxy pipe. The instrument is epoxy grouted into a 38 mm diameter borehole and monitored for strain response during overcoring. The fully encapsulated strain gauges and lead wires provide immunity from the effects of ground water and drilling water during overcoring. The 10 mm long strain gauges minimize the influence of rock grain size. Carefully selected strain gauge orientation produces a statistically powerful result of high sensitivity when strain response is analyzed to determine the stress tensor.

Installation:

The HI cell is installed into a 38 mm diameter hole by filling the hollow body of the cell with a preformulated epoxy cement and extruding the cement with a piston when the cell is at target depth. The piston is activated by pushing the body of the cell, via installation rods, over the piston. A trip wire within the cell registers completion of extrusion.

Multiple rubber seals confine the grout flow to around the cell. The gradual flow of excess grout pre-wets and washes the borehole, forcing loose particles or moisture away from the critical area of rock to be bonded.

The gauges are thus fully bonded 1.5-2.0 mm from the borehole wall, for which allowance is made in the data reduction program.

Digital Strain Gauge Read Out Unit:

Although the HI cell can, and has been successfully datalogged during overcoring, most users to date have monitored the cell with the use of a portable strain gauge indicator. Of this type, a purpose designed strain gauge read-out unit supplied by RST has been found to be the most convenient to use.

Twelve Strain Gauge HI cell:

The conventional, nine strain gauge HI cell has been proven to be completely adequate for stress measure in isotropic rock. A development of the conventional cell has been to provide an additional three strain gauges, situated at different orientations to provide more information for measurements in anisotropic rock. For those users who require it, this version of the cell supplies a greater degree of redundancy for measurement in isotropic rock.

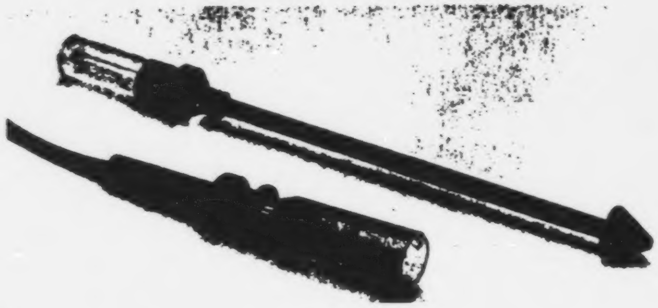
Overcoring:

Monitoring of the strain response during overcoring is via a multi-conductor cable from the HI cell which runs through the drilling rods and a modified water swivel to a strain indicator. The ability to record strain gauge information during overcoring provides valuable information, and indicates conditions such as the onset of core cracking, cell de-bonding or inelastic response of the rock. The retrieved overcored section of rock containing the cell can be restressed in a biaxial pressure chamber to derive the actual rock properties of Young's Modulus and Poisson's Ratio.

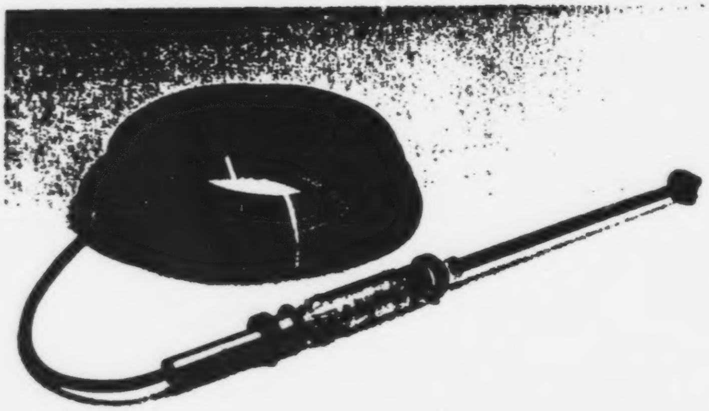
Hollow Inclusion

Some of the countries in which the HI Cell has been used include:

Australia • Austria • Canada • Equador • Germany • Hong Kong • Italy • New Zealand • Portugal • South Africa • Sweden • Switzerland • Thailand • United Kingdom • U.S.A. • Zambia



Stress Cell



Thermistor or Dummy Strain Gauge:

An accurate temperature measuring thermistor is available as an option to provide checks of possible temperature movements at the HI cell site. Alternatively, a high precision 120 ohm resistor can be placed into the cell to act as a passive dummy strain gauge.

Stress Change Monitoring:

The HI cell has been successfully used as a rock stress change monitoring instrument. It has been found that the cells are best suited to monitoring compressive or tensile, stress changes which occur over days or weeks rather than gradual changes. Cells installed in-situ have behaved reliably for periods in excess of two years.

Following installation a HI cell generally behaves as though it is subjected to a small biaxial compression with time. The magnitude of this response decreases with time, and it is recommended that cells should be installed 1-3 months prior to the expected occurrence of of any stress change to reduce errors in the determination thereof.
As it is a triaxial instrument, the HI cell will return useful data when installed into a borehole drilled at any orientation to the principal stress directions.

Data Reduction:

Three stress calculation programs are available:
1. An isotropic analysis, written in BASIC, suitable for running on HP85/86 computers.
2. An isotropic analysis, written in FORTRAN, suitable for running on IBMPC (or compatible) or on mini/mainframe computers.
3. An anisotropic and isotropic analysis, based on the theory developed by Professor Bernard Amadie, suitable for running on an IBM PC or compatible computer.

Accessories:

1. Epoxy Grout: A range of epoxy grouts is available suitable for bonding the HI cell into the borehole. They cover various temperature ranges so there is a need to specify the expected temperature range of use.

They are moisture tolerant, have a useful life after mixing of 30-45 minutes and once extruded around the cell, set hard in 6-30 hours, depending on temperature conditions. They are available in preformulated packs for single installations.

2. Installation Tool: Incorporates a robust dual-castor trolley used to clean the EX borehole then place the HI cell at target depth. It includes a mercury switch attachment for accurate orientation. The castors are adjustable to accommodate varying borehole diameter.

3. Installation Rods: Stainless steel rods with positive locking connections which attach to the installation tool. Standard rod length is 1.8m but may be varied on special order.

4. Biaxial Pressure Chamber: Used for determination of the deformation modulus and Poisson's Ratio of the overcore surrounding the cell. It incorporates a steel pressure chamber and a neoprene sleeve into which the vore slides very simply. The associated hydraulic hand pump and 30 MPa pressure gauge and hoses are also available. Specify core diameter when ordering.

5. Field Manual: A comprehensive field manual prepared to assist personnel conducting stress measurements with the HI cell is available. It covers:-

Site Selection
Equipment Requirements
Installation
Biaxial Test
Hole Drilling Equipment
Programme Planning
Drilling Procedure
Overcoring
Tools and Equipment

(A check list is included for each of the critical steps.)

6. Dummy HI Cell: This is basically a standard HI cell which does not contain strain gauges or have a data cable attached. This is useful for conducting grout extrusion tests for situations where unusual conditions may apply.

7. Data Acquisition Systems: The electrical circuit of the HI cell was designed under the assumption that only one strain gauge would be connected into a Wheatetone bridge (for reading purposes) at any time.

In datalogging situations where all strain gauges are powered simultaneously (either for short duration or continuously) the two common wires for all active strain gauges cannot be used.

RST can advise and supply to users the correct type of strain gauge bridge completion network to enable a HI cell to be successfully datalogged. RST can also supply complete data acquisition systems to suit the datalogging requirements of HI cells.

8. Technical Publications: A comprehensive list of technical papers and reports pertaining to the use and performance of the HI cell, is available from RST.

Technical Specifications:

Strain Gauges:
Gauge length: 10 mm
Gauge resistance: 120 ohms
Gauge factor: 2.07-2.11
Circuit: three-wire quarter bridge

Borehole Size:
38 mm diameter (EX or EXT) for HI cell
140-150 mm diameter for overcore (100 mm diameter satisfactory in good coring conditions).

Operating Range:
(Present field experience)
Temperature: 5° C – 50° C
Stress range: Up to 100 MPa
Accuracy: $\frac{\text{Standard Error of Stress}}{E} = 10$ ppm

ANZSI* TRIAXIAL STRESS CELL

FOR STRESS MEASUREMENT IN SOFT ROCK

Features:

- ★ Determines the complete stress tensor from one overcoring operation
- ★ Will operate successfully in material with low tensile strength such as coal
- ★ A pressuremeter type test can be carried out before overcoring to determine the elastic modulus of the rock
- ★ Strain changes are monitored during the overcoring process
- ★ Successful field tests conducted in sub-bituminous coal
- ★ Can be used as a triaxial stress change monitoring instrument

Principle of Operation:

The ANZSI cell is an inflatable triaxial soft inclusion strain measuring instrument for use in conjuction with the borehole overcoring technique for rock stress measurement.

Electrical resistance strain gauges located on an outer membrane surface are directly bonded onto the wall of a 38mm diameter pilot hole.

The instrument can be inflated to a pressure of ± 1 MPa to conduct a pressure test in-situ to determine the elastic modulus of the surrounding material. This can be carried out before the overcoring process takes place.

The relatively low stiffness of the ANZSI cell ensures that large, radial tensile stresses are not developed at the instrument - rock interface during stress relief. This reduces the possibility of instrument - to - rock debonding or tensile failure of the rock itself adjacent to the interface.

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* Auckland New Zealand Soft Inclusion Cell.

Construction:

The instrument consists of a polyurethane elastomer membrane mounted onto a PVC cylinder. Nine electrical resistance strain gauges are flush mounted onto the membrane surface. 5 mm long strain gauges are used to measure strain at each point and all electrical connections are made within the waterproof membrane material. The strain gauges are mounted on slightly raised humps on the surface of the membrane so as to attain a uniform pressure distribution on the strain gauge when it is inflated against the borehole wall.

Installation:

The 38mm diameter pilot hole is first cleaned and dried. Cement is applied to the recessed section of the membrane. The instrument is inserted into the pilot hole, oriented, and then inflated to a pressure of 300-600KPa. The strain gauges are pressed into contact with the rock and the epoxy cement is forced into a thin film, bonding the gauge to the borehole.

Pressure Test:

A pressure test can be conducted after the cement has cured. Generally, the pressure is cycled several times up to 1MPa while the strain gauges are being monitored. This confirms that the gauges are correctly bonded to the rock and the data obtained is used to calculate the rock modulus.

Overcoring:

The electrical cable is threaded through the drill rods and an adapted water swivel so that all strain gauges can be monitored during overcoring. The complete set of stress relief curves can be very useful, particularly in closely jointed rock where the probability of gauges bonding across a joint is high. If a suitably intact core is recovered, a standard biaxial test can be conducted to determine the elastic modulus and Poisson's ratio.

Stress Change Monitoring:

A modified instrument can be used for monitoring long term stress changes in rock where the assumption of linear elastic behaviour is valid. The ability to conduct a pressure test in-situ is useful in this application as it provides confirmation of the correct strain gauge operation and properties of the local rock.

Technical Specifications:

Strain Gauge length	5 mm
resistance	120 ohms
gauge factor	2.00
circuit	three wire quarter bridge
Borehole Size:	
for ANZSI cell EX or EXT size	(38mm diameter)
for overcore	100-150mm diameter

Accessories:

- ★ installation equipment including pressure pump and gauge. Note that the installation tool and rods are identical to those supplied for the CSIRO Hollow Inclusion stress measurement cell.
- ★ the most appropriate cement with which to bond the cell to the borehole wall. Please specify conditions of application.
- ★ biaxial pressure chamber. Used for determination of the deformation modulus and Poisson's ratio of the overcore surrounding the cell.
- ★ data reduction program which runs on an IBM PC or compatible computer, or a HP 85/86 series computer.
- ★ portable digital strain gauge indicator.

PRINTED IN CANADA 9/87

APPENDIX B

Manufacturer's information on
Rocagil AL

STRATA

ROCAGIL AL

Chemical grout for rock and concrete consolidation or watertightening.

The ROCAGIL AL is a low viscosity mixture of an acrylic monomer and an aqueous dispersion resin.

Following the addition of a catalyst, the ROCAGIL AL yields, after a controlled time, an elastic and cohesive material, highly sticky on rocks, coal and concrete.

Thanks to this property, the injection of ROCAGIL AL into the voids of soils or cracks of rocks and concrete permits an increase in their cohesiveness and watertightness.

INTRODUCTION.

The purpose of grouting is to solidify soft soils or rocks and to stop water seepage by injecting grouting materials under pressure into the soil or the cracks of the rocks.

The penetration of a chemical grout into the voids of soils or the cracks of rocks mainly depends on :

- the permeability of the ground or the size of the cracks.
- the viscosity of the grout.
- the injection pressure.

1) PHYSICAL AND CHEMICAL PROPERTIES.

The ROCAGIL AL grouting agent is composed of two components :

- the resin which is offered under two qualities :
  - ROCAGIL AL 6 allowing shorter than 1 hour setting time.
  - ROCAGIL AL 7 allowing up to 1 hour setting time.
- the catalyst which is offered in two forms :
  - liquid
  - powder

1.1. Resin.

	ROCAGIL AL 6	ROCAGIL AL 7
- Appearance	White aqueous emulsion	
- Density at 20° C	1,05 g/cm3	1,05 g/cm3
- pH	8,3	7
- Viscosity at 20° C	20/22 cP	14/16 cP

1.2. Catalyst (Ammonium Persulfate)

- Powder : white, highly water-soluble, strong oxidising agent.
- Liquid : 6 % active matter aqueous solution.

pH = 3.
Density : ~ 1 g/cm3 at 20° C.

2) PACKAGING - STORAGE.

2.1. ROCAGIL AL 6 or AL 7 resin :

- 46 kg net plastic barrels.

The shelf life of the product will be not less than six months if stored :

- out of sunlight.
- under temperature conditions from 5° C to 30° C.

2.2. CATALYST - Ammonium Persulfate :

- Powder :
  - 5 kg cardboard boxes containing 50 x 100 g polyethylene bags.
  - 10 kg cardboard boxes containing 10 x 1 kg polyethylene bags.

The Ammonium Persulfate powder must be kept out of contact with humidity and stored as a combustive material.

- Liquid :
  - 8 kg net plastic barrels.

The shelf life of the aqueous solution of Ammonium Persulfate is a maximum of 2 months.

3) GROUT FORMULATION.

The ROCAGIL AL grout must be prepared differently according the form of Catalyst which is to be used.

Usual Formulas.

3.1. Powder form Catalyst :

ROCAGIL AL	92 litres
WATER	8 litres
CATALYST (A.P.)	0,5 kg

Dissolve first the A.P. in water then add this solution to the ROCAGIL AL resin and mix.

3.2. Liquid form Catalyst :

ROCAGIL AL	92 litres
CATALYST (A.P. Solution)	8 litres

Mix together the two liquids for at least one minute before injection.

4) MAIN PROPERTIES OF THE ROCAGIL AL GROUT.

4.1. Viscosity - penetrability.

The ROCAGIL AL grouts are characterized by their low viscosity which remains constant until the polymerisation reaction occurs and they solidify.

Thanks to this property, the ROCAGIL AL grouts can be injected up to the point where solidification occurs.

4.2. Setting time.

The setting time is the period between the mixing of the resin and the catalyst and solidification of the grout.

When solidification occurs, the viscosity of the grout suddenly increases as well as temperature.

The setting time of the ROCAGIL AL grout can be influenced by various factors such as :

- Temperature of the grout.

For a fixed catalyst ratio, the setting time decreases if the temperature increases.

Temperature (°C)	Setting time	
	ROCAGIL AL 6	ROCAGIL AL 7
20°	30-40 mn	20 h
25°	20-25 mn	16 h
30°	15-20 mn	10 h
45°	5 mn	4 h

- Catalyst concentration.

For different temperatures of final grout adjust the setting time by changin the catalyst concentration.

- Tested formula :

(ROCAGIL AL 6 : 92 litres
(EAU : 8 litres

Ammonium Persulfate \ Température	10°C	20°C	30°C	40°C
0,2 kg	184 mn	60 mn	23 mn	11 mn
0,4 kg	116 mn	40 mn	20 mn	7 mn
0,5 kg	100 mn	30 mn	14 mn	6 mn
0,6 kg	90 mn	20 mn	11 mn	5 mn
0,8 kg	71 mn	16 mn	8 mn	4 mn
1,0 kg	69 mn	13 mn	6 mn	3 mn

- Soluble air into the grout.

In the case of quick mixing, soluble air can increase the setting time.

- Ultraviolet rays.

Are strong initiators of the polymerisation reaction. So the ROCAGIL AL solutions must be kept out of sunlight.

- Prolonged contact with certain metals, such as iron and copper, have an accelerating effect on the polymerisation reaction. So the use of plastic or stainless steel vessels is recommended to prepare the grout.

5) PROPERTIES OF THE POLYMERISED ROCAGIL AL.

The maximum characteristics are obtained a few hours after polymerisation.

5.1. Appearance.

White, elastic and adherent solid.

5.2. Solubility.

Not soluble in water nor in hydrocarbons.

5.3. Shrinkage - swelling.

The ROCAGIL AL polymerised solid may swell in water.

Inversely it may dry and shrink but, will swell again if poured into water.

5.4. Resistance to chemicals.

The ROCAGIL AL polymerised solid is very resistant to diluted acids and bases.

5.5. Mechanical properties.

- tensile strength measured on ROCAGIL AL polymerised dumb-bell sample.

	Tensile strength	Elongation
ROCAGIL AL 6	13 bars	180 %
ROCAGIL AL 7	17 bars	340 %

- simple compression strength.

Measured on cylindrical sample of injected sand (Ø 4 cm - h 8 cm).

- Fontainebleau sand sample : 15 - 20 bars
- G3 sand sample : 5 - 10 bars

6) ADDITIVES FOR SPECIAL GROUTS.

6.1. Increasing the viscosity.

The viscosity of the ROCAGIL AL grout can be increased by the addition of 0,01 to 0,1 % of RHODOPOL 23.

The ROCAGIL AL grout becomes pseudoplastic. It fluidifies under shearing and instantly recovers the initial viscosity when the shear stress is removed (cf RHODOPOL 23 leaflet).

6.2. Increasing the density.

The density of the ROCAGIL AL grout can be increased by incorporating Barium Sulphate (density 4.2).

RHODOPOL 23 can also be used in such a case to stabilize the suspension.

6.3. Shrinkage.

The use of fillers (< 100 μ) permits a reduction in the shrinkage of the polymerised ROCAGIL AL.

7) PREPARATION OF THE ROCAGIL AL GROUT.

7.1. Discontinuous method.

Resin, catalyst and water are mixed together in a plastic or stainless steel tank. Then the grout is pumped into the ground via the injection pipe.

This method needs simple equipment but :

- it is discontinuous.
- it is not possible to use short setting times.
- it is difficult to vary the setting time during the injection of a batch.
- a danger of polymerisation in the equipment exists if the pumping rate decreases.

7.2. Continuous method.

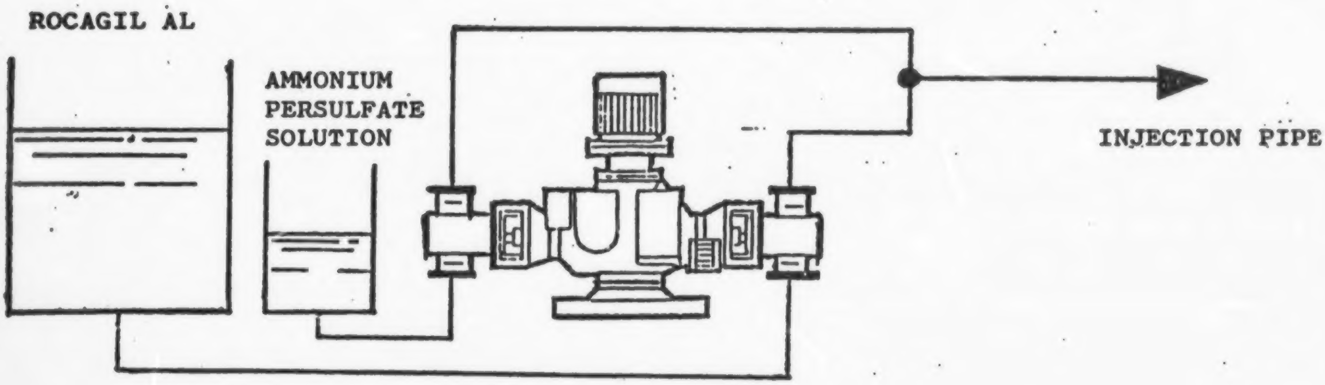
A double-barrelled volumetrical pump must be used.

The first barrel feeds a small amount of catalyst solution in proportion to the flow of the ROCAGIL AL resin which is fed by the other barrel.

The two products are mixed together under pressure and injected into the ground.

By changing the flow rate of the A.P. solution barrel, it is possible to vary the setting time.

The grout must not be allowed to polymerise in the pump.



VARIABLE VOLUME PUMP

8) PRECAUTIONS FOR USE.

The grouting of ROCAGIL AL must be done by specialists.

8.1. Handling of the ROCAGIL AL resin and catalysts.

Care should be taken in the handling of ROCAGIL AL and A.P.

Special equipments must be worn by operators = rubber gloves, protective eyes glasses, water proof coats, boots.

Should products be splashed on the skin, the operator must wash immediatly with fresh water.

Empty packages must not be refilled.

In coal mines, only the liquid from catalyst is permitted.

8.2. Handling of the ROCAGIL AL grout.

Fresh water must be at the disposal of workers at the preparation and injection sites.

Prevent the grout from splashing on the skin by wearing special equipment.

9) APPLICATIONS.

9.1. Mining applications.

- Faults
- Coal flowing
- Coal face/tunnel junction crossing
- Schist strata in coal faces

For such uses in coal mines the main advantages of the ROCAGIL AL Grout are :

- very light smell
- non-inflammable product
- total solubility into water
- low viscosity, so good injection properties

The polymerised ROCAGIL AL has a high resiliency effect and is not permeable to water or gas.

9.2. Public works applications.

Prevention of water leakages in soils, rocks and concrete structures.

The information given in this data sheet is the result of our own research and experience.

It is given in good faith but cannot in any circumstances constitute a guarantee of our part nor engage our responsibility.

rhône-poulenc chimie fine
Département Lubrification - Détergence
Spécialités Industrielles

Division de Rhône-Poulenc Industries
21, rue Jean Goujon - F 75360 PARIS cedex 08
Tél. (1) 256.40.00 - Telex : 640 100 F
R. C. Paris B 300 847 621

APPENDIX C

List of Experts Contacted

LIST OF EXPERTS CONTACTED

Dr. Tim Aston, Cape Breton Coal Research Laboratory, Nova Scotia
(902) 564-7670

John F. Abel, Golden, Colorado
(303) 273-3709

Douglas J. Belshaw, Solinst Canada Ltd.
(416) 335-5611

Dr. Fred Carr, Jim Walter Resources Inc., Birmingham, Alabama

Dr. Adrian Crawford, Dept. of Civil Engineering, University of Toronto
(416) 978-3115

Dr. Fred Djahanguiri, Mining Engineer, Geocon Canada, Mississauga
(416) 673-1664

Dr. Kenneth Dunham, British Mining Consultants
01144 623 441 444

Professor M. Dusseault, University of Waterloo
(519) 888-4590

Professor Ian Farmer, University of Arizona
(602) 621-4994

Steve Forgeron, Chief Geologist, CBDC, Nova Scotia
(902) 564-2939

Dr. Winton Gale, Australian Coal Industry Research Laboratory
011 61 42834 499

Dr. Richard Goodman, University of California
(415) 642-5526

Kenan Hanna, USBM, Denver, Colorado
(303) 236-7563

Khamis Haramy, Mining Engineer, USBM, Denver, Colorado
(303) 236-0721

Ferri P. Hassani, McGill University
(514) 398-4377

J. R. Hoskins, Dept. of Metallurgical and Mining Engineering,
University of Idaho
(208) 885-6376

Mike Jenkins, U.S.B.M.
(509) 484-1610

Joe Jones, Saskatchewan Research Council
(306) 933-5400

Prof. Reuben Karol, Chemical Grouting Consultant, Princeton, N.J.
(609) 520-0010

Dr. K.C. Lau, Strata Engineering Corp.
(416) 441-2560

Dr. Paul Lu, U.S.B.M.
(303) 236-0745

Dr. M.A. Mahtab
Res. - (914) 626-4319

Dr. H. Maleki, Agapito Associates
(303) 242-4220

Don MacDonald, Rhone Poulenc Canada Ltd.
(416) 821-4450 Ext. 420

Kevin MacDonald
(201) 460-6005

Ken W. Mills, Consulting Engineer, Auckland, New Zealand
011 64 4 858603

Dennis Mraz, Saskatoon, Saskatchewan
(306) 955-0240

Osman A. Momah, Noranda Mines, Point Claire, Que.
(514) 697-6640

Tom Morgon, Consultant on in-situ stress measurement
(505) 672-3091

Dr. Parviz Mottahed, PCS, Saskatoon, Saskatchewan
(306) 933-8535

Professor Duk Park, University of Alabama, Tascaloosa
(205) 348-6578

Professor Syd Peng, West Virginia University
(304) 293-5695

Doug Reid, Design Engineer, Engineered Instruments Inc.
(306) 955-0240

Dr. Robert Sandquist, O.S.U.
(614) 263-4600

Dr. Barry Sellers, Geokon Inc., Lebanon, New Hampshire
(603) 448-1562

Professor Doug Stead, University of Saskatchewan
(306) 966-5684

Robert Straghan, R.S. Technical Instruments Ltd.
(604) 941-9155

Professor Barry N. Whittaker, University of Nottingham
0602 506 101 ext. 2620